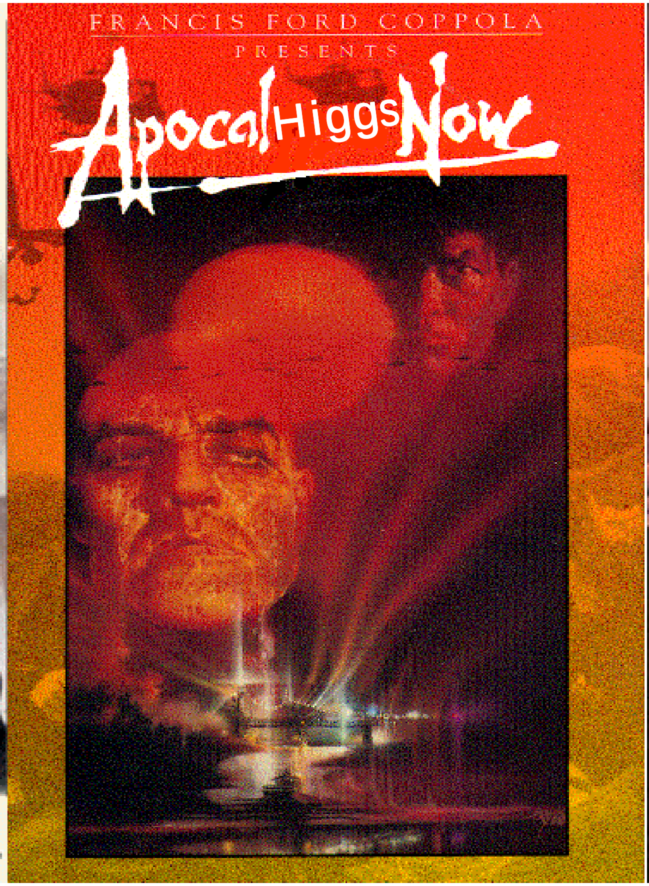
Direct and Indirect Probes of EWSB
in e^+e^- Annihilation (LEP and SLC)

Patrick Janot, CERN

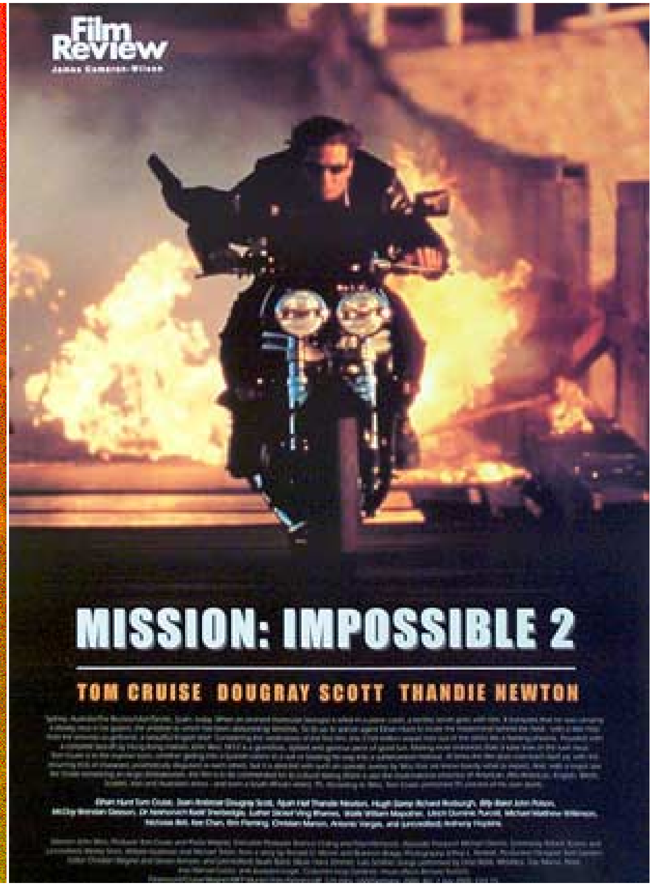
Outline:

First Lecture:

Second Lecture:



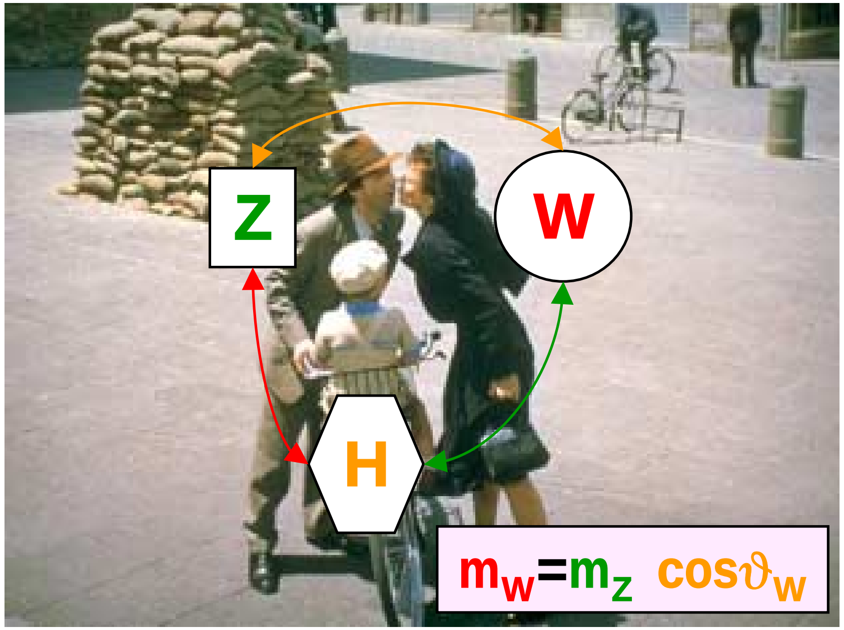
Third Lecture:



Indirect Probes of EWSB at LEP and SLC

Common Goals of LEP and SLC:

- Check the internal consistency of the Standard Model of Electroweak interactions (Z & W studies);
- Test with **precision** the predictions of Electroweak Symmetry Breaking (m_W vs m_Z);
- Predict heavy particle masses and new physics scale (m_{top}, m_H, Λ?)



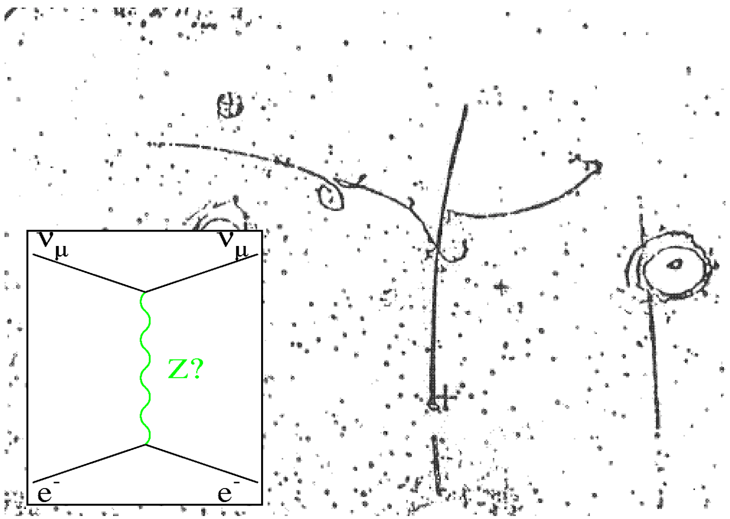
First Lecture Outline:

1. Brief History & Overview
2. Brief Theory Reminder:
   Why is Precision needed?
3. List of "Electroweak" Observables
4. A few Precision Measurements
   - Z Lineshape & Beam Energy (LEP)
   - Left-Right Asymmetry and Beam Polarization (SLC)
   - Heavy Flavour Rates (LEP&SLC)
   - W mass (LEP)
5. The top mass prediction
6. The Higgs boson mass prediction
7. Standard Model consistency

A Little Bit of History

1967: Electroweak unification, with W, Z and H (Glashow, Weinberg, Salam);

1973: Discovery of neutral currents in $\nu_\mu e$ scattering (Gargamelle, CERN)

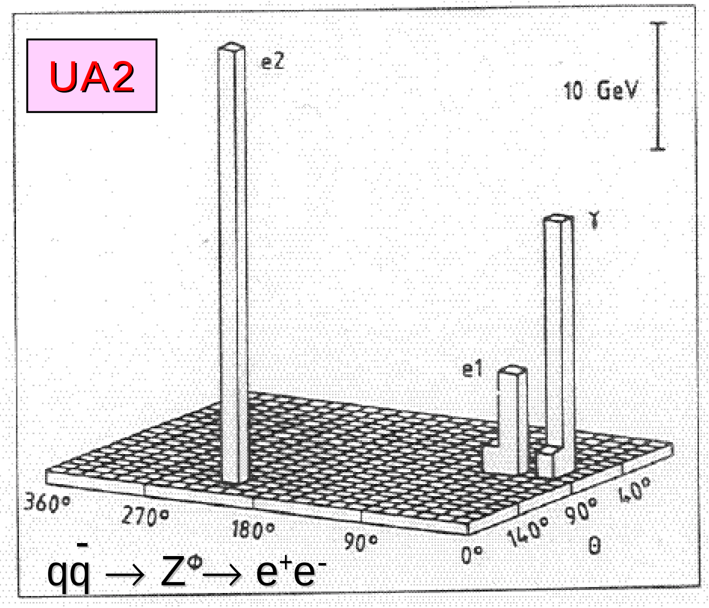


1974: Complete formulation of the standard model with $SU(2)_W \times U(1)_Y$ (Illiopoulos)

1981: The CERN SpS becomes a $p\bar{p}$ collider; LEP and SLC approved before W/Z discovery;

1983: W and Z discovery (UA1, UA2); LEP and SLC construction start;

First Z detected in the world:



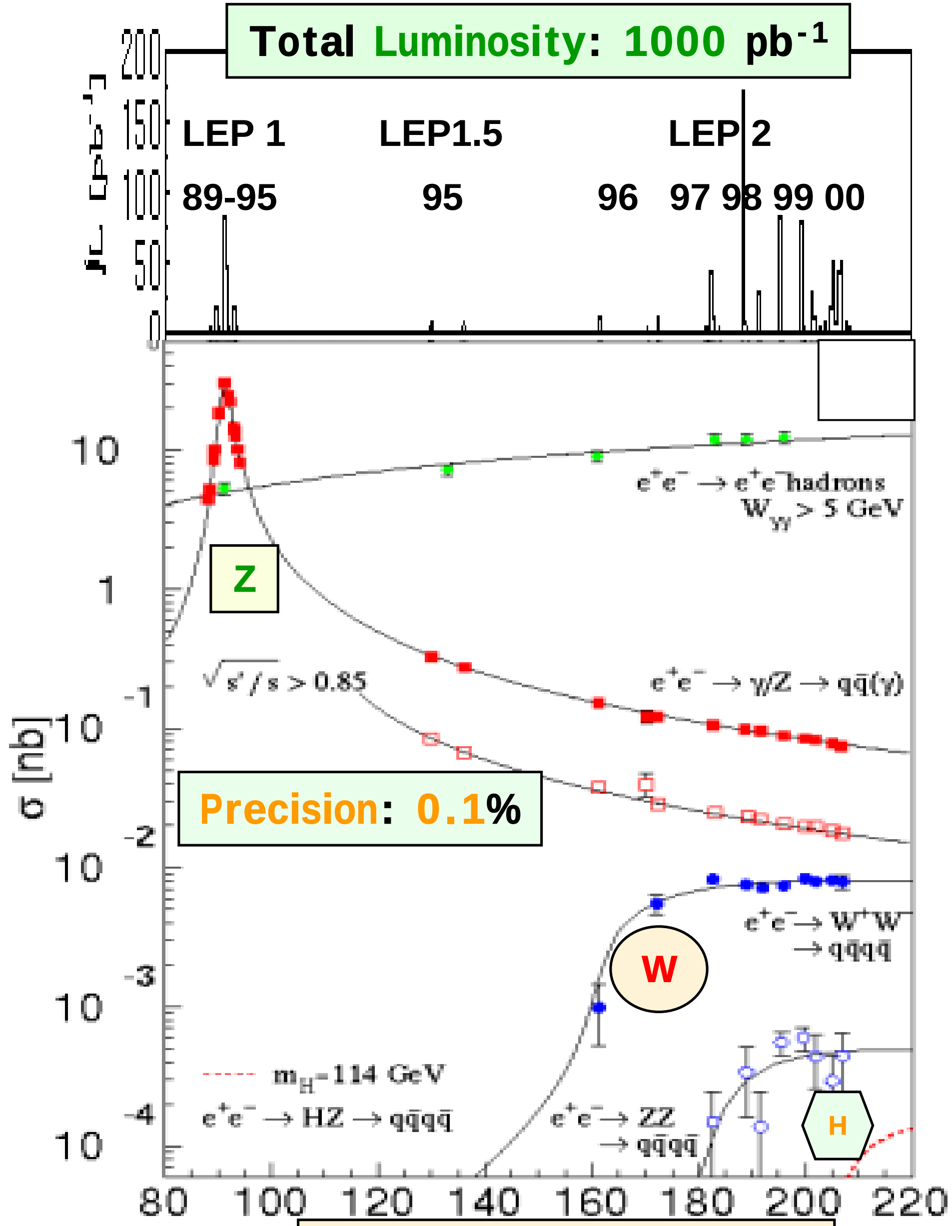
1989: First collisions in LEP and SLC; Precision tests of the SM (m_{top});

1995: Discovery of the top (FNAL); Precision tests of the SM (m_H);

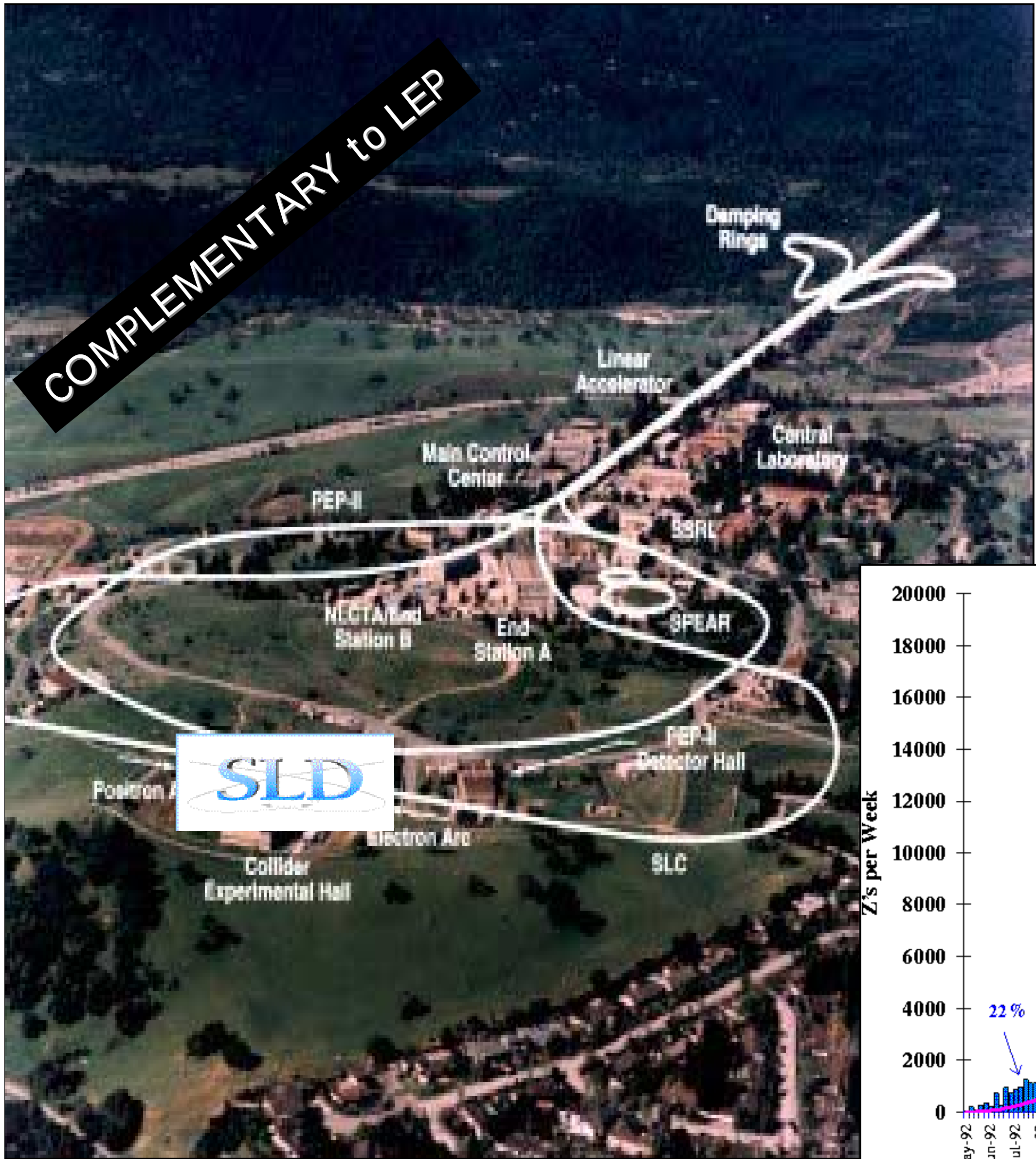
2000: First hints of the Higgs boson?

LEP Overview: Luminosity, Energy, Precision

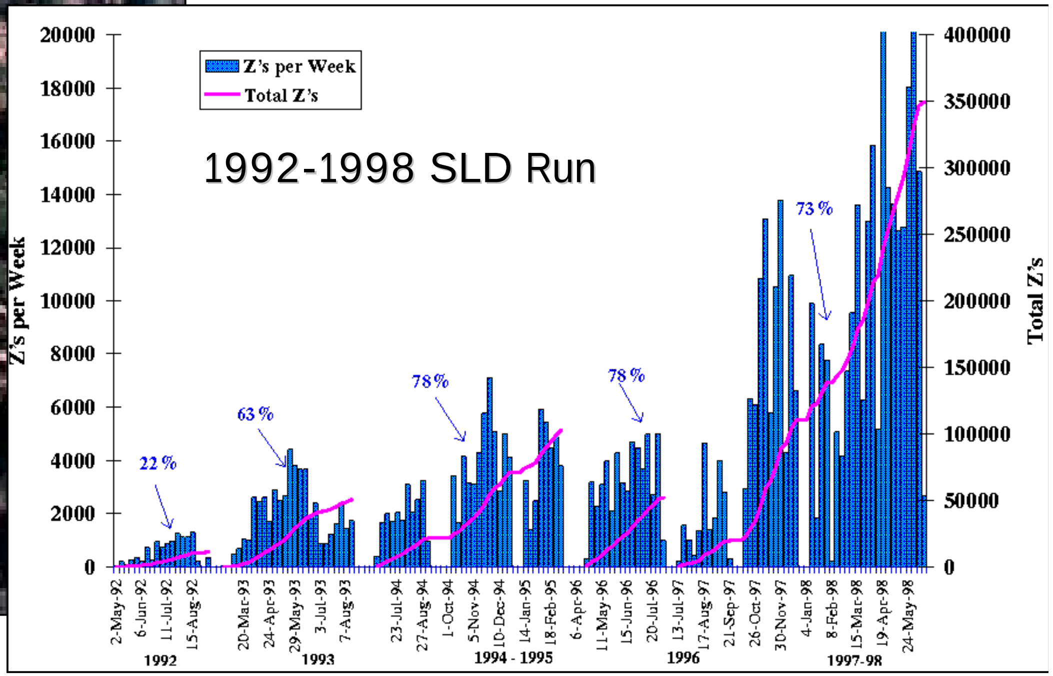
- Conventional collider e^+e^- ring;
- Energy upgradeable;
- Energy measurable;
- Four detectors (A,L,D,O);
- Large luminosity;
- 20 Million Z events.



Stanford Linear Collider Overview

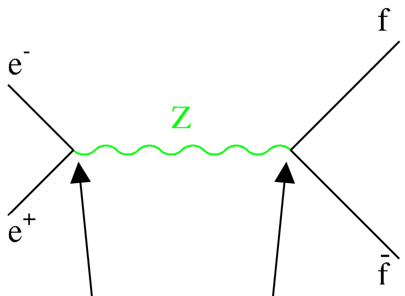


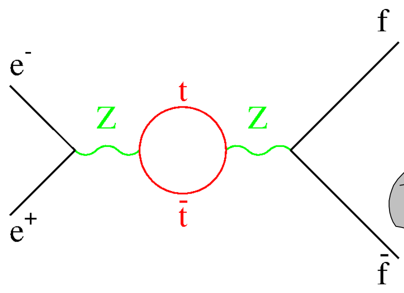
- First high energy e^+e^- "linear" collider (with arcs);
- Reduced luminosity;
- 73% polarized electron beam;
- Small transverse beam sizes;
- Small beam pipe;
- Only one detector (MarkII, SLD)
- 350,000 Z events

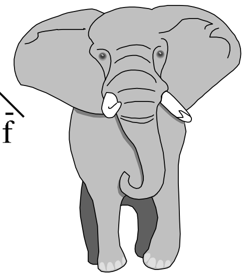


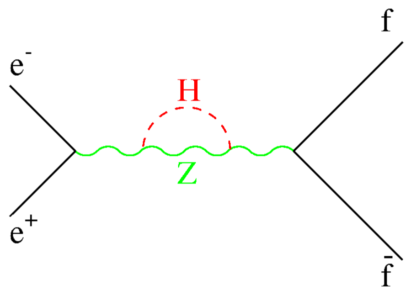
Why is Precision Needed?

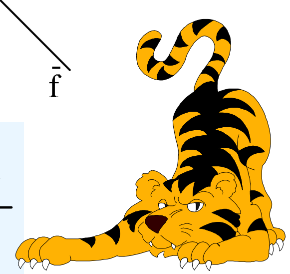
Electroweak Observables (i.e., related to W and Z) sensitive to vacuum polarization effects:











L Couplings (v+a)
≠
R Couplings (v-a)

$$\frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2} \approx 1\%$$

$$-\frac{\alpha}{4\pi}\mathrm{Log}\frac{m_H^2}{m_Z^2}$$

0.1% Precision needed!

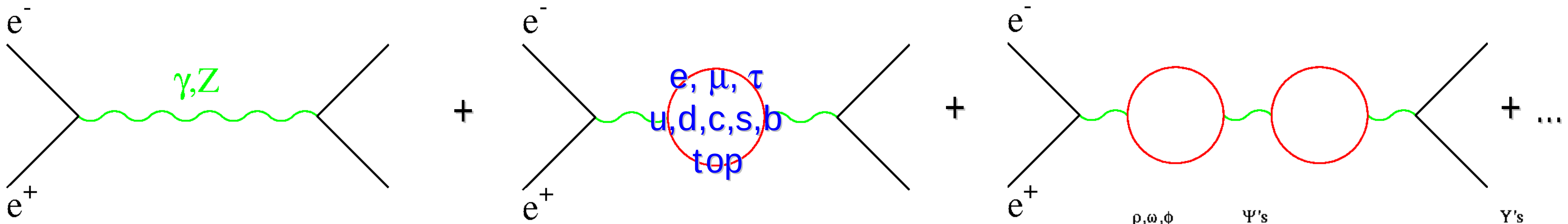
Tree-Level →	Corrected
$a_0 = \pm 1/2$	$a = a_0(1+\Delta\rho)$
$v_0 = a_0(1-4\lvert Q\rvert \sin^2\theta_W)$	$v = a(1-4\lvert Q\rvert \sin^2\theta_W^{eff})$
$\sin^2\theta_W = 1 - m_W^2/m_Z^2$ ($m_W = m_Z \cos\theta_W$)	$\sin^2\theta_W^{eff} = 1 - m_W^2/m_Z^2(1+\Delta\rho)$
$\alpha(0) = 1/137.0359895(61)$	$\alpha(m_Z) = 1/128.968(27)$

with
$$\Delta\rho = \frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2} - \frac{\alpha}{4\pi}\mathrm{Log}\frac{m_H^2}{m_Z^2} + \cdots$$

- Determine $\Delta\rho$ and $\sin^2\theta_W$ from LEP/SLD data;
- Predict m_{top} and m_W;
- Compare with direct measurements;
- Predict m_H;
- Compare with direct measurements.

Quantum Corrections to $\alpha(m_Z)$ (I)

Common quantum (energy-dependent) corrections to γ and Z can be absorbed in a redefinition of the QED coupling constant α (also called "running")

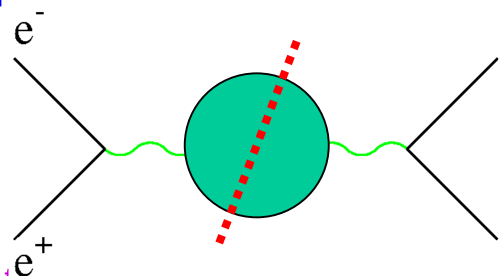


$$\alpha(s) = \frac{\alpha_{\rm QED}(0)}{1 - \Delta\alpha_{\rm leptons} - \Delta\alpha^{(5)}_{\rm had} - \Delta\alpha_{\rm top}}$$

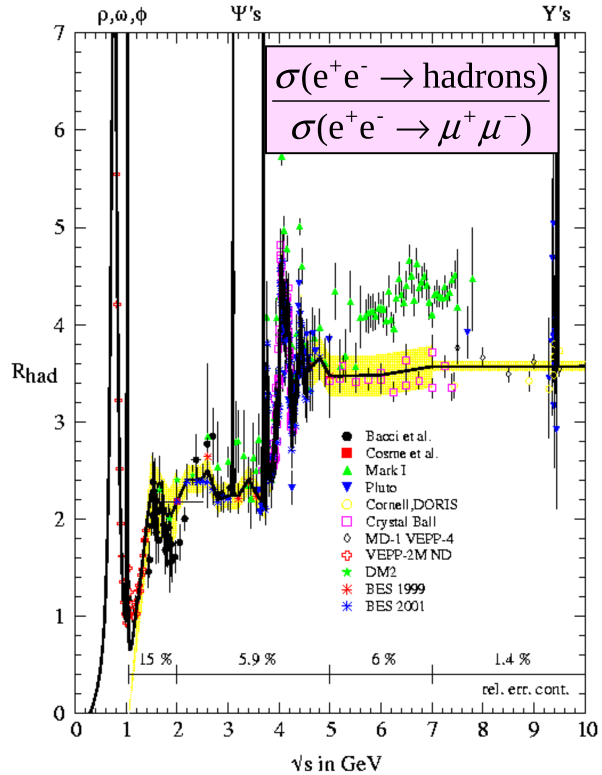
Precise QED Calculation

Small, $\propto \log m_{top}$ Calculate

Evaluate from:



$e^+e^- \to$ hadrons at various $\sqrt{s}$ + QCD predictions

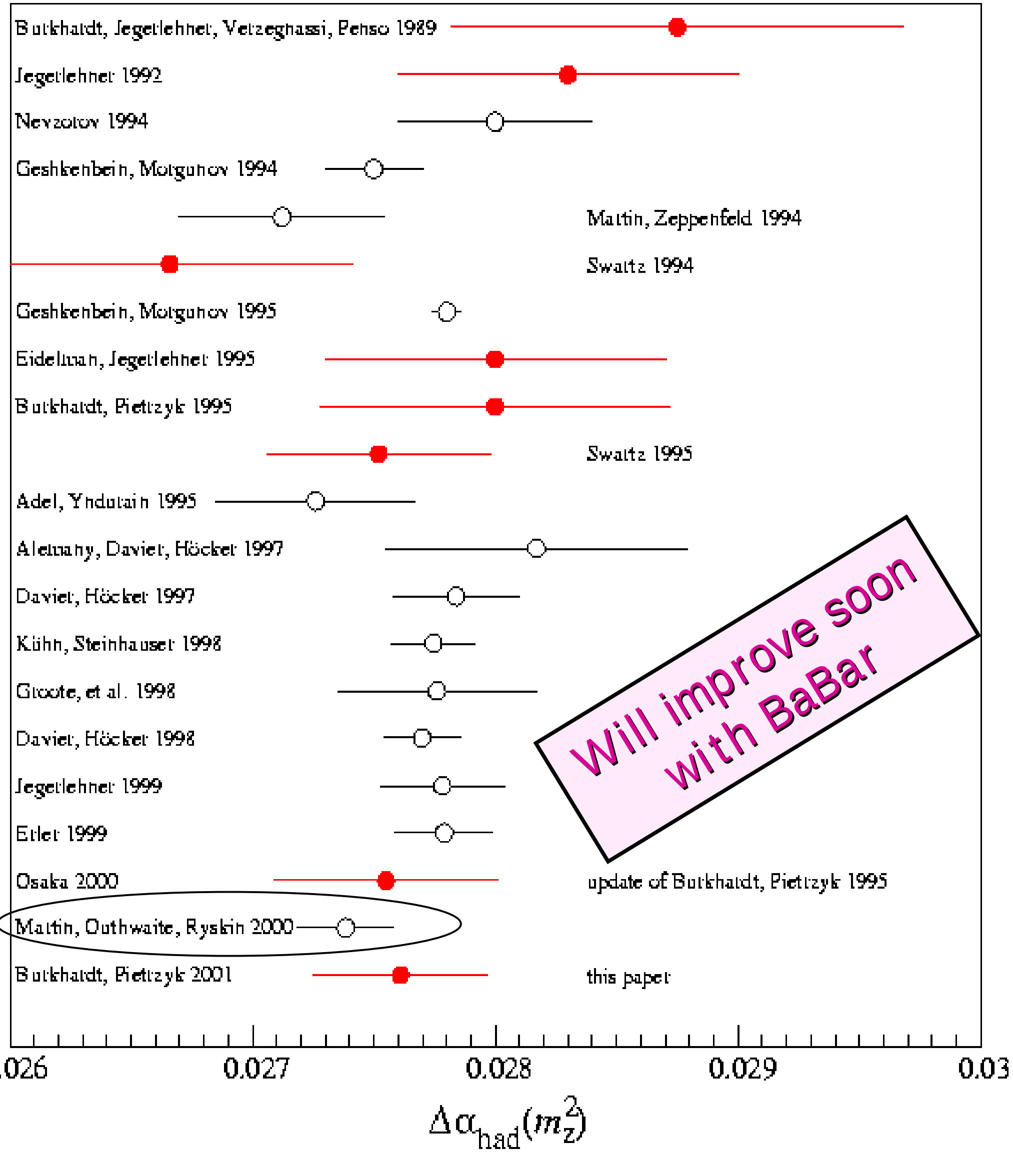


Quantum Corrections to $\alpha(m_Z)$ (II)

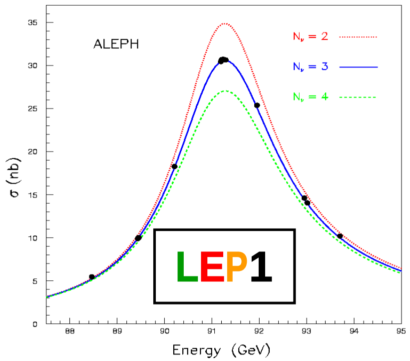
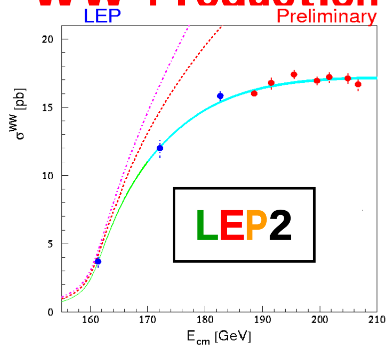
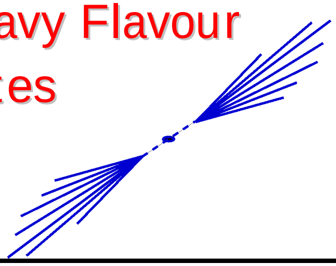
Results more and more precise:

- ❑ More e^+e^- data at low energy (in particular with BES)
- ❑ Better knowledge of QCD at low energy (proven by hadronic τ decays studied at LEP)
- ❑ $\Delta\alpha^{(5)}_{had}(m_Z) = 0.02738 \pm 0.00020$
- ❑ $\alpha(m_Z) = 1/128.968(27)$

  (most precise, most up-to-date)

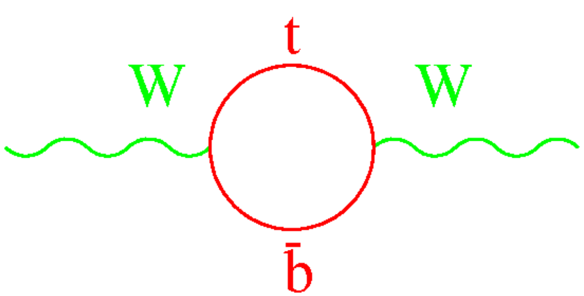


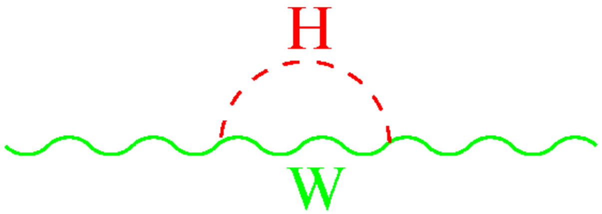
Precision Electroweak Observables (I)

Experiment	Observable	Main technology	Precision	Physics output
Z Lineshape 	m_Z Γ_Z σ_{peak} $R_\ell = \frac{\Gamma_{hadron}}{\Gamma_{lepton}}$	Absolute beam energy (+ ISR QED calculations) Relative beam energy (+ ISR ...) Absolute luminosity Final state identification	2.10^{-5} 10^{-3} 10^{-3} $1.2.10^{-3}$	Input! $\Delta\rho, \alpha_s, N_\nu$ N_ν α_s, m_{top}
WW Production 	m_W	- Absolute *Beam energy *Luminosity - Final state Identification	5.10^{-4}	m_H vs m_{top}
Heavy Flavour Rates 	$R_b = \frac{\Gamma_{b\bar{b}}}{\Gamma_{hadron}}$ $R_\ell = \frac{\Gamma_{c\bar{c}}}{\Gamma_{hadron}}$	b-tagging (Vertex detector) c-tagging (mostly SLD)	3.10^{-3} 2%	m_{top}

Dependence on m_{top}, m_H of m_W and R_b

1. W mass: Specific Vacuum Polarization



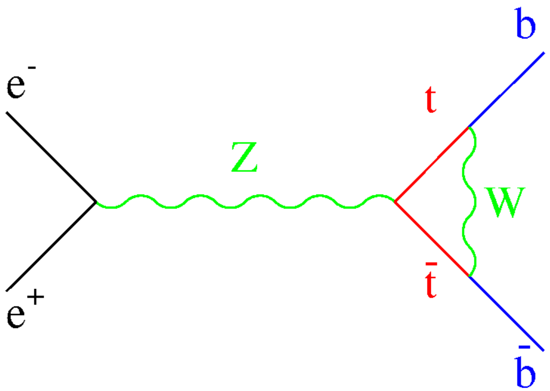


$(m_W/m_Z)^2$
$\downarrow$
$(m_W/m_Z)^2 \times (1+\Delta r)$

$$\Delta r = -\frac{\cos^2\vartheta_W}{\sin^2\vartheta_W}\Delta\rho + \frac{\alpha}{3\pi}\left[\frac{1}{2} - \frac{1}{3}\frac{\sin^2\vartheta_W}{1-\tan^2\vartheta_W}\right]\mathrm{Log}\,\frac{m_H^2}{m_Z^2} + \cdots$$

(Different m_{top}, m_H dependence)

2. $Z \to b\bar{b}$ decay rate: Specific Vertex Correction



$R_b \to R_b\,(1+\delta_{Vb})$

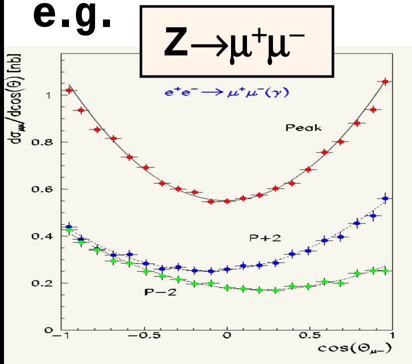
$$\delta_{Vb} = -\frac{20}{13}\alpha\frac{m_t^2}{m_Z^2} \approx 5\%$$

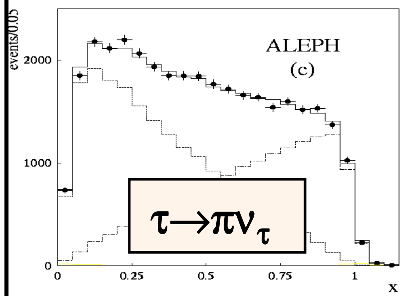
0.5% Precision needed

(No m_H !)

Precision Electroweak Observables (II)

Experiment	Observable	Main technology	Precision	Physics output
Parity Violation L Couplings (v+a) ≠ R couplings (v-a) ⇓ Asymmetries e.g. $Z \to \mu^+\mu^-$	$A_{FB}^{\ell} = \frac{3}{4} A_e A_\ell$	Precision of the Detectors	$2.2\ 10^{-3}$	$A_f = \frac{2v_f/a_f}{1+(v_f/a_f)^2}$
	$A_{FB}^{b} = \frac{3}{4} A_e A_b$	LEP	$1.3\ 10^{-3}$	↓
	$A_{FB}^{c} = \frac{3}{4} A_e A_c$		$3.4\ 10^{-3}$	$1-4\lvert Q_i\rvert \sin^2\theta_W^{eff}$
	$\langle P_\tau \rangle = A_\tau$	Precise Energy High Luminosity	$1.8\ 10^{-3}$	$\sin^2\theta_W^{eff}$
	$A_{FB}^{pol}(\tau) = A_e$	+ b-Tagging τ-selection	$2.0\ 10^{-3}$	to 5.10^{-4}
	⋮	⋮		m_W
$\tau \to \pi \nu_\tau$	$A_{LR} = P_e \times A_e$	Polarized Beam (SLC only)	$1.1.10^{-3}$	Consistency Checks!

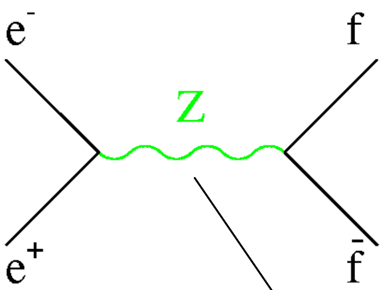




$$\sin^2\theta_W = 1 - m_W^2/m_Z^2(1+\Delta\rho)$$

The Z Lineshape at LEP

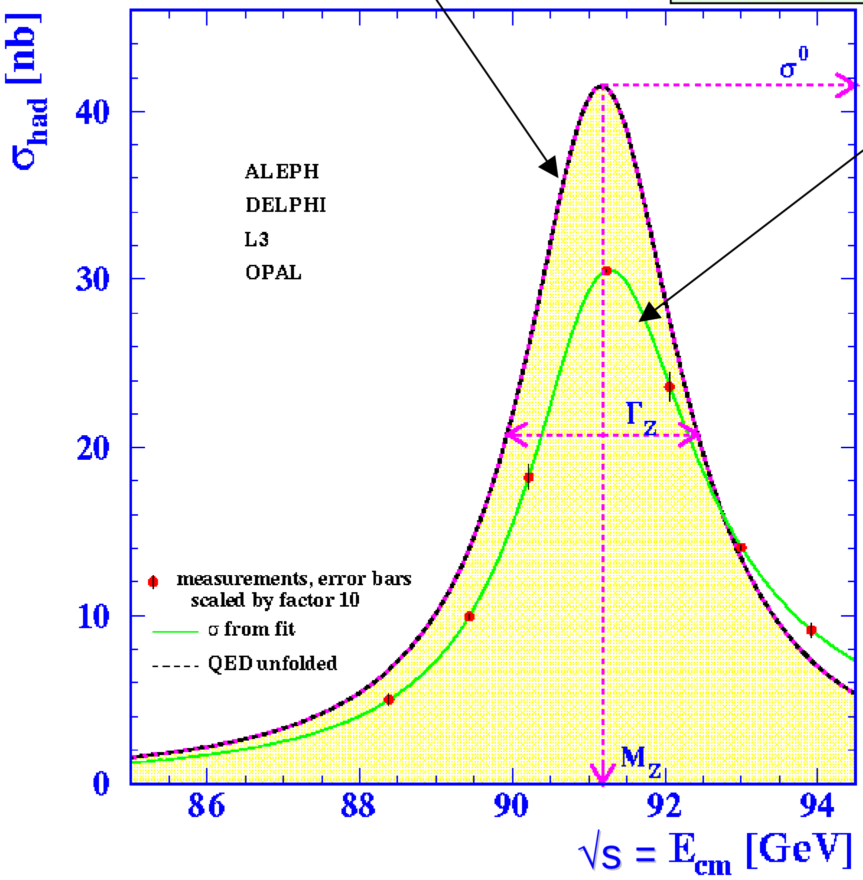
At tree-level:



$$\sigma_{f\bar{f}} \approx \sigma^0_{f\bar{f}} \times \frac{s\Gamma_Z^2}{(s-m_Z^2)^2 + s^2\Gamma_Z^2/m_Z^2} \quad \text{with}$$

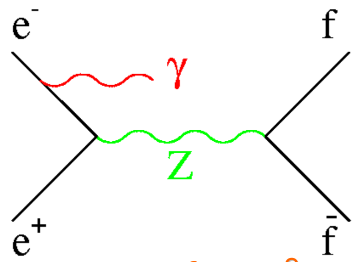
$$\sigma^0_{f\bar{f}} = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{ff}}{\Gamma_Z^2} \quad \text{and} \quad \Gamma_{ff} = \frac{G_F m_Z^3}{6\pi\sqrt{2}} \times (v_f^2 + a_f^2) \times N_{col}$$

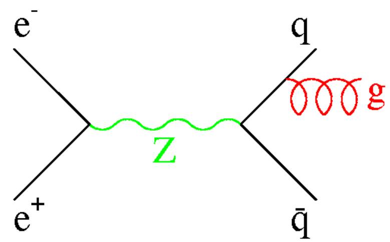
$\propto (1+\Delta\rho)$



1) Measure σ and s

2) Correct for QED and QCD





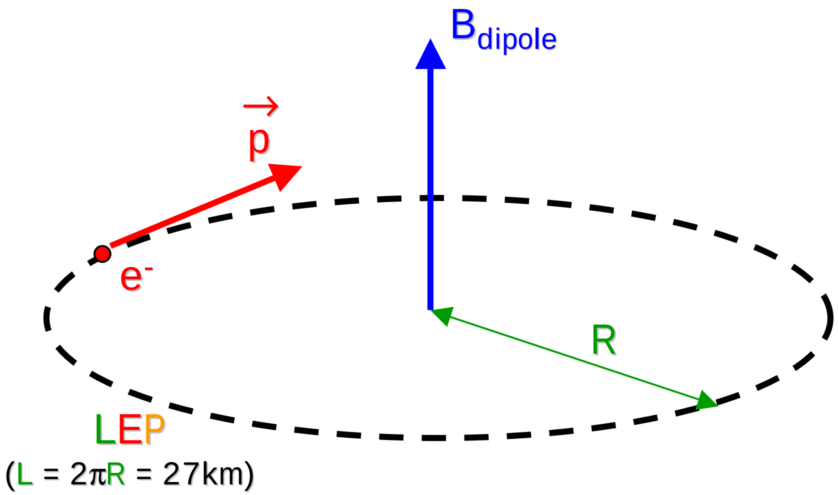
-30% for σ^0
+200 MeV for m_Z

+4% for Γ_{qq}

3) Fit for the Z parameters
(mass, total width, peak cross section and partial widths)

Measurement of the LEP Beam Energy (I)

Approximation: LEP is a circular ring immersed in a uniform magnetic field:



$$E \sim p = e\,B\,R = (e/2\pi)\,B\,L$$

In real life:

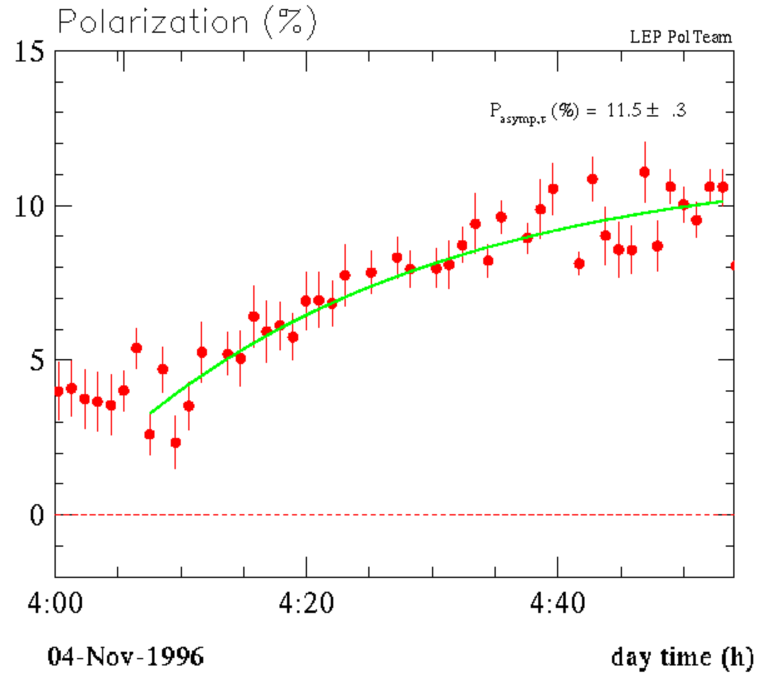
B non-uniform, ring not circular

$$E = \frac{e}{2\pi} \oint_{LEP} B \, \mathrm{d}l$$

To be measured

1) The electrons get transversally polarized (i.e., their spin tends to align with B), but

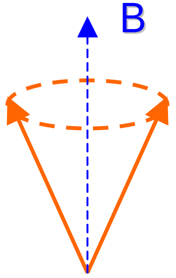
- Process very sensitive to imperfections (→ slow, typically hours, and limited to o(10%) polarization)



- Process very sensitive to beam-beam interactions (→ one beam, no polarization in collisions)

Measurement of the LEP Beam Energy (II)

2) The spin precesses around B with a frequency proportional to B.



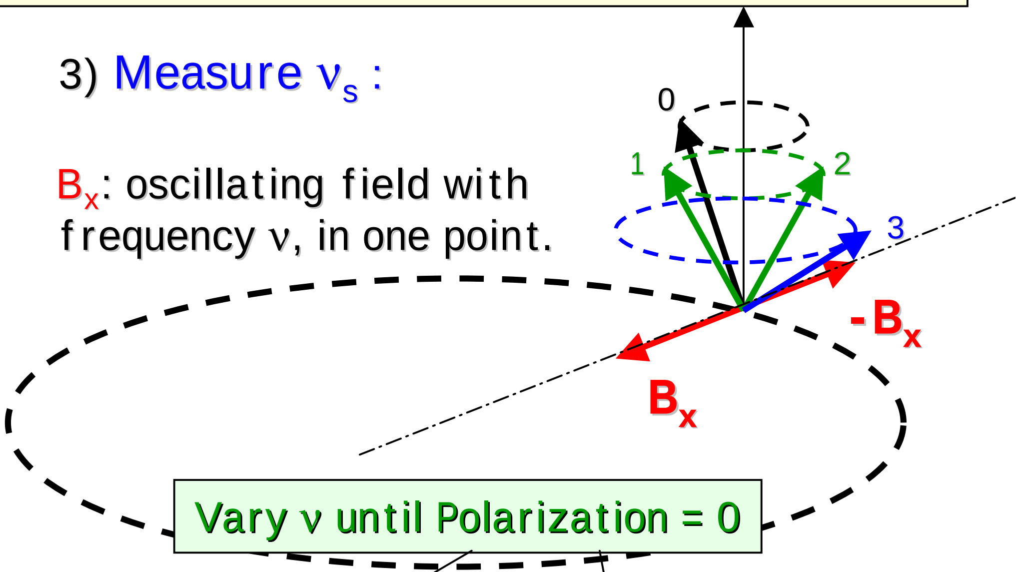
The number of revolutions for each LEP turn is thus proportional to B L (in fact, to ∫ B dl, and then to E_{beam})

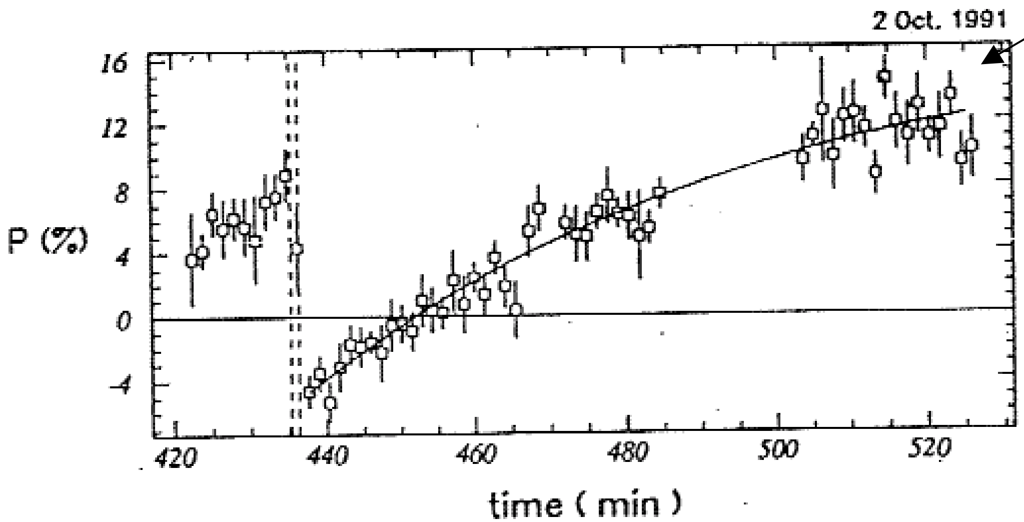
$$\nu_s = \frac{g_e - 2}{2m_e} \times E_{\text{beam}}$$

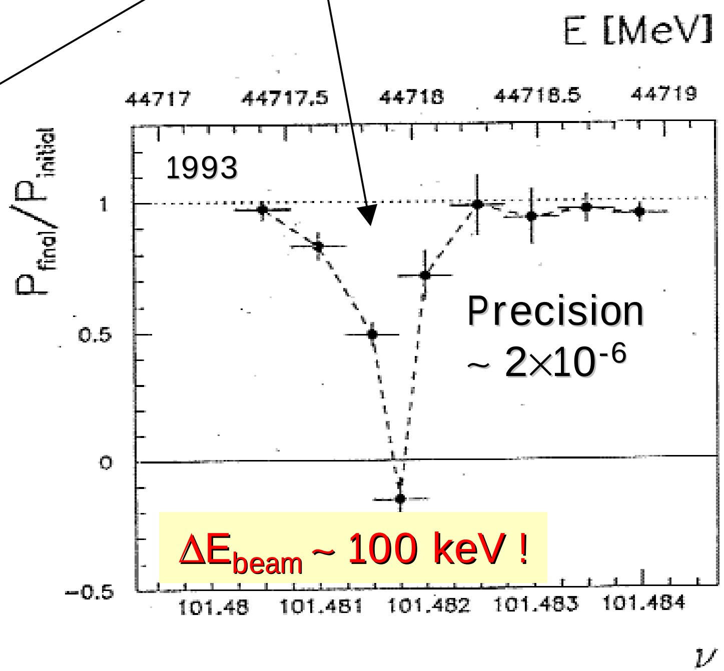
101.5	Peak-2
103.5	Peak
105.5	Peak+2

3) Measure ν_s :

B_x: oscillating field with frequency ν, in one point.

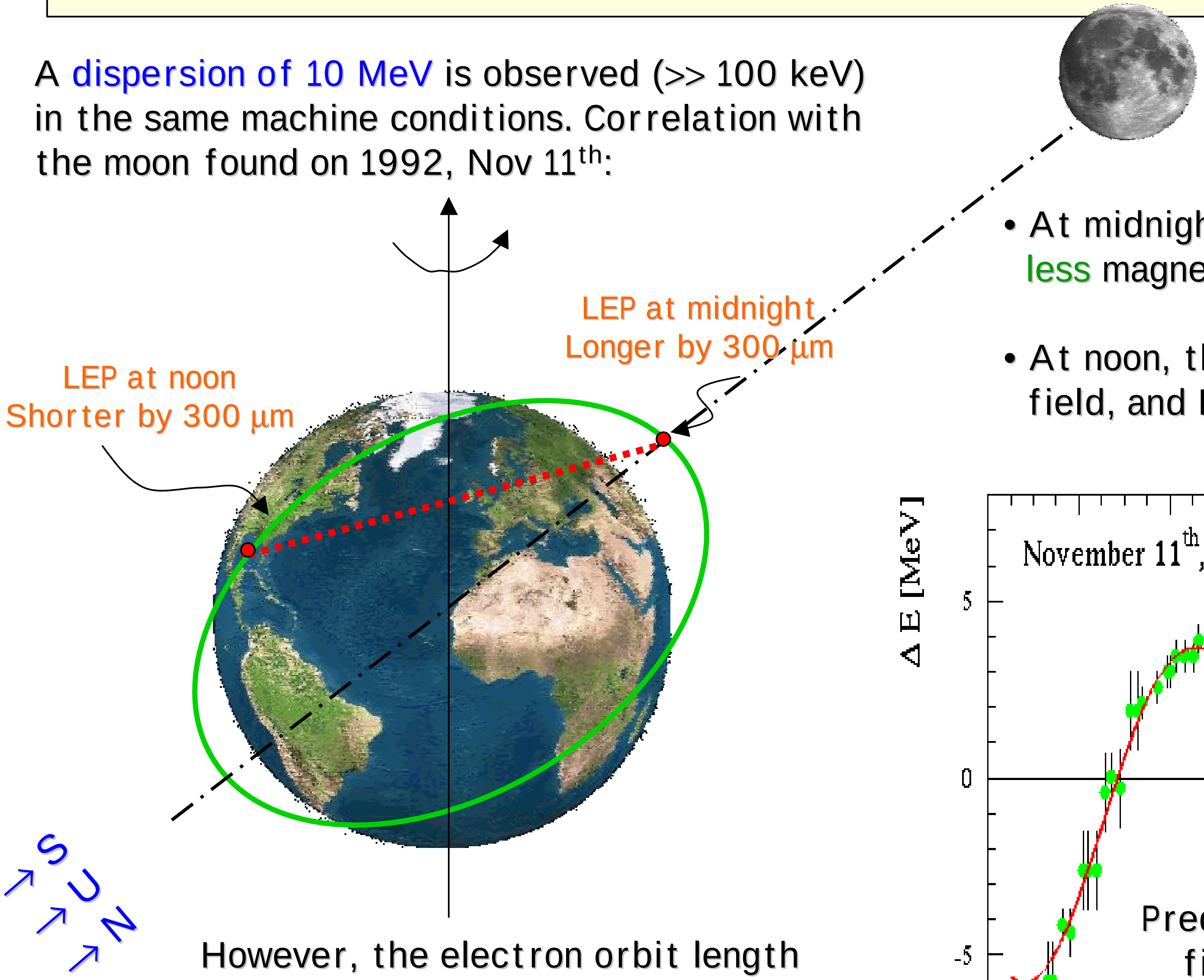




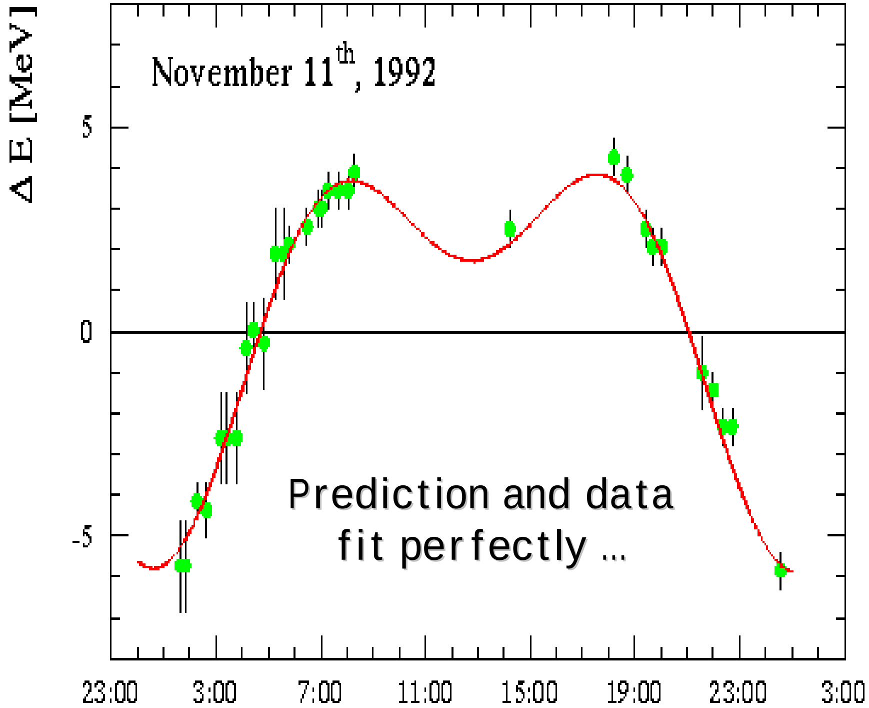


Measurement of the LEP Beam Energy (III)

A dispersion of 10 MeV is observed (>> 100 keV) in the same machine conditions. Correlation with the moon found on 1992, Nov 11th:



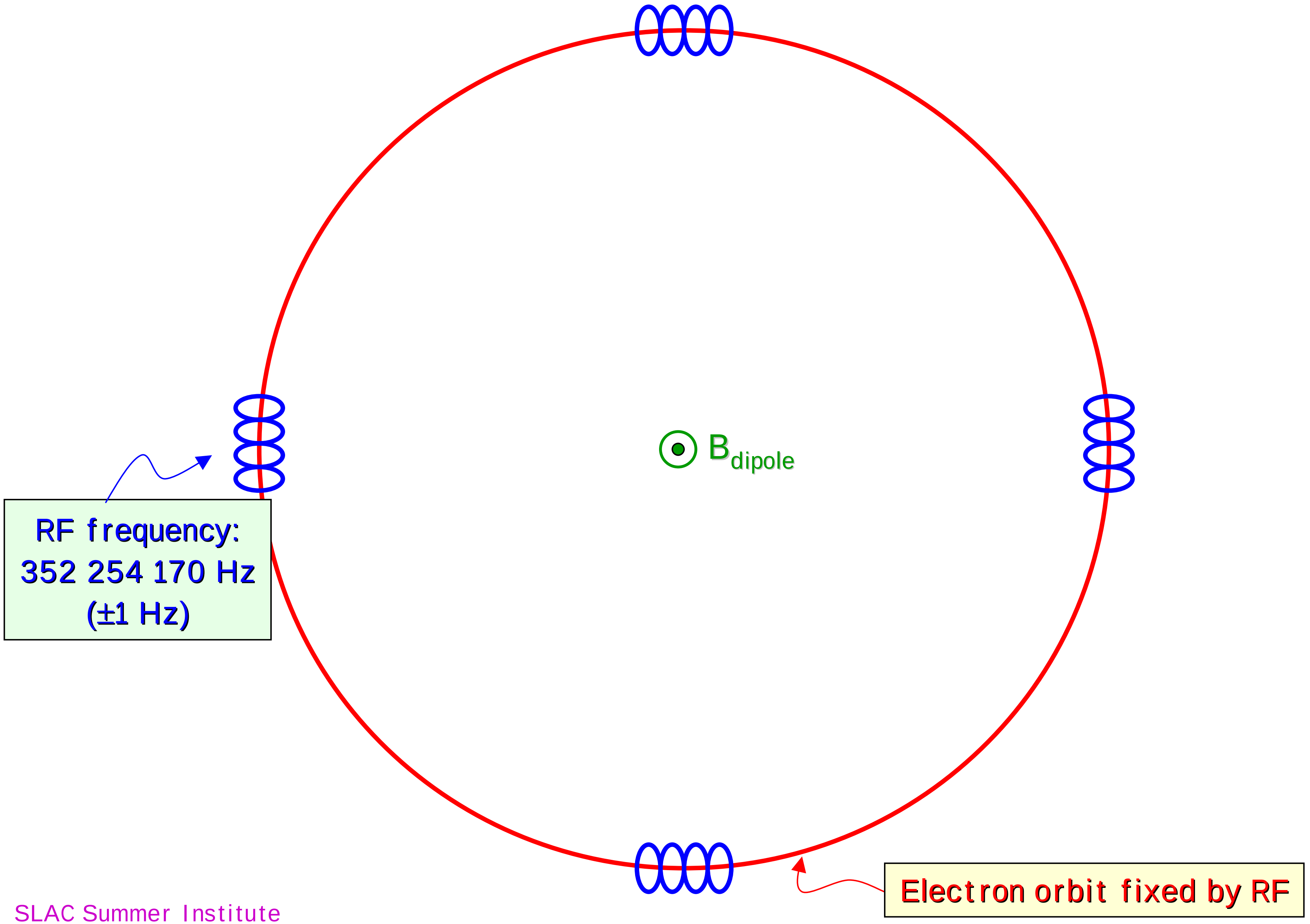
- At midnight, the electrons see less magnetic field, E is smaller;
- At noon, they see more magnetic field, and E is larger.

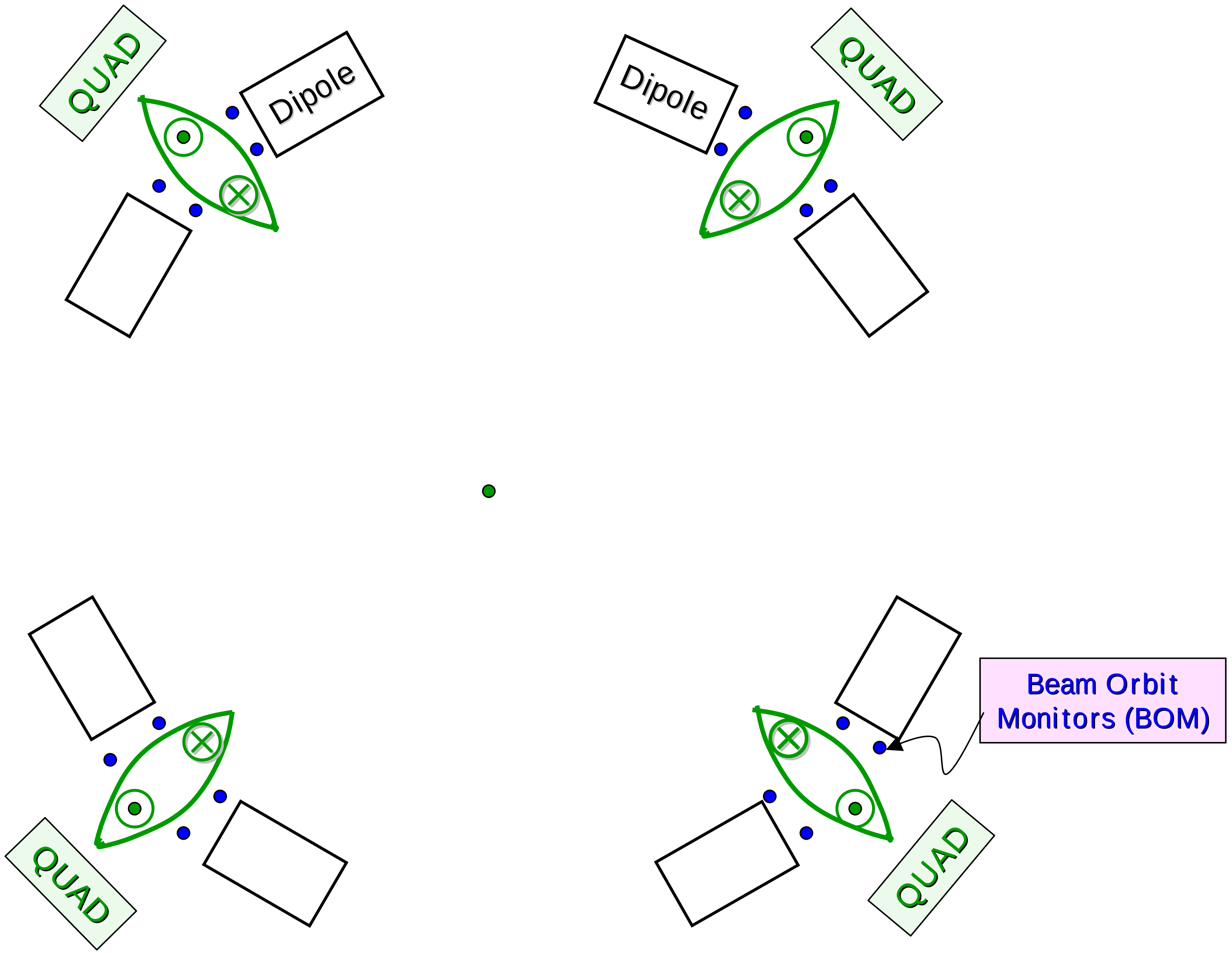


However, the electron orbit length is fixed by the RF frequency:

$$L = c \times \Delta t$$

Measurement of the LEP Beam Energy (IV)

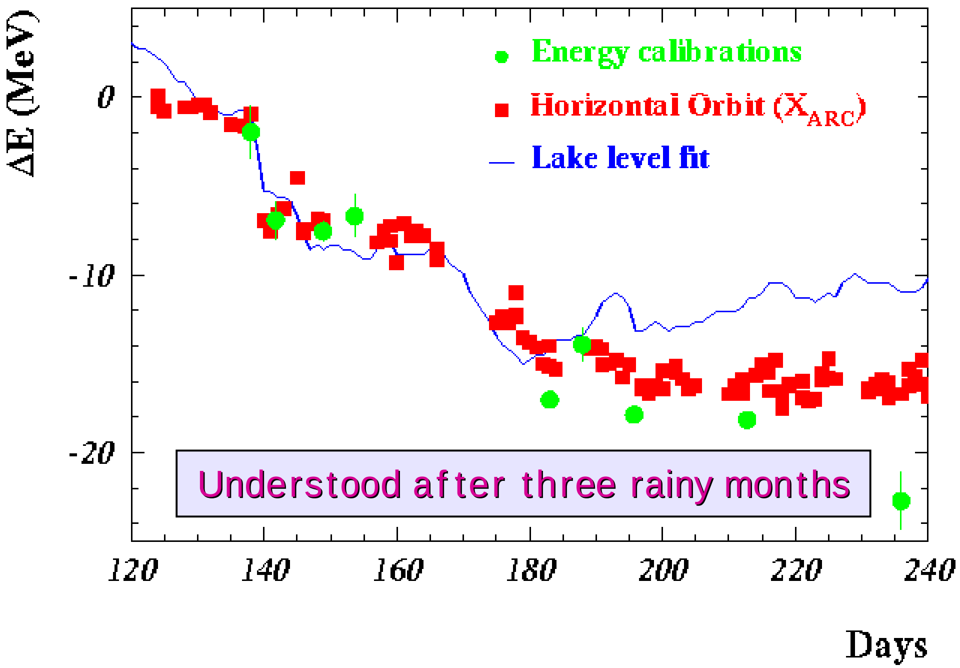



QUAD
Dipole
Dipole
QUAD
QUAD
QUAD
Beam Orbit
Monitors (BOM)

Measurement of the LEP Beam Energy (V)

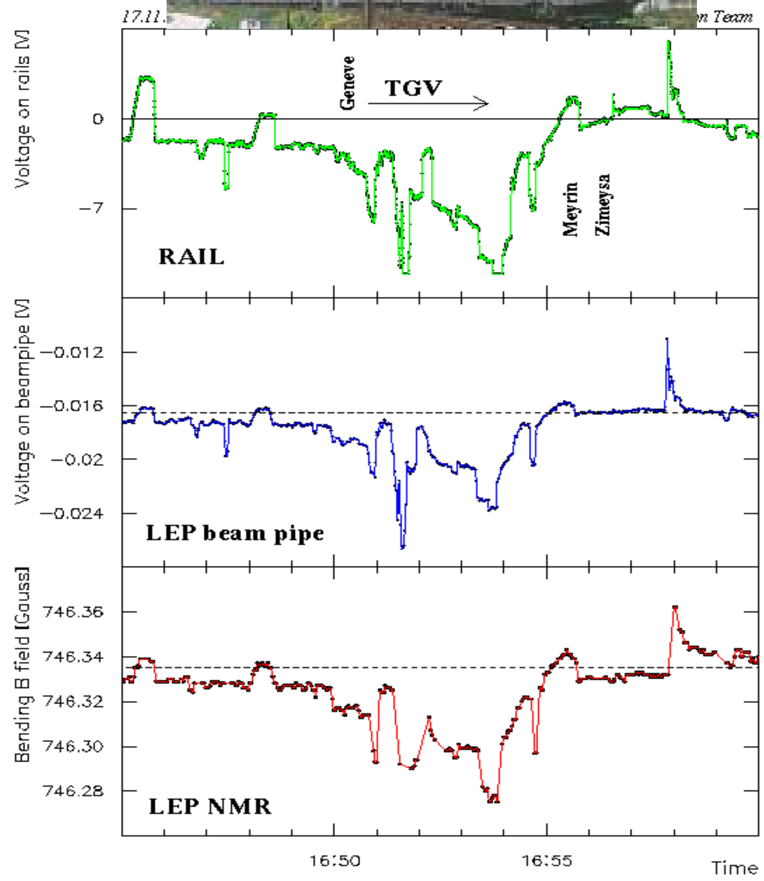
Other 10 MeV-ish effects understood even later:

- Effect of the rain: water pressure in the mountains change LEP circumference;
  (controlled with the BOM's)



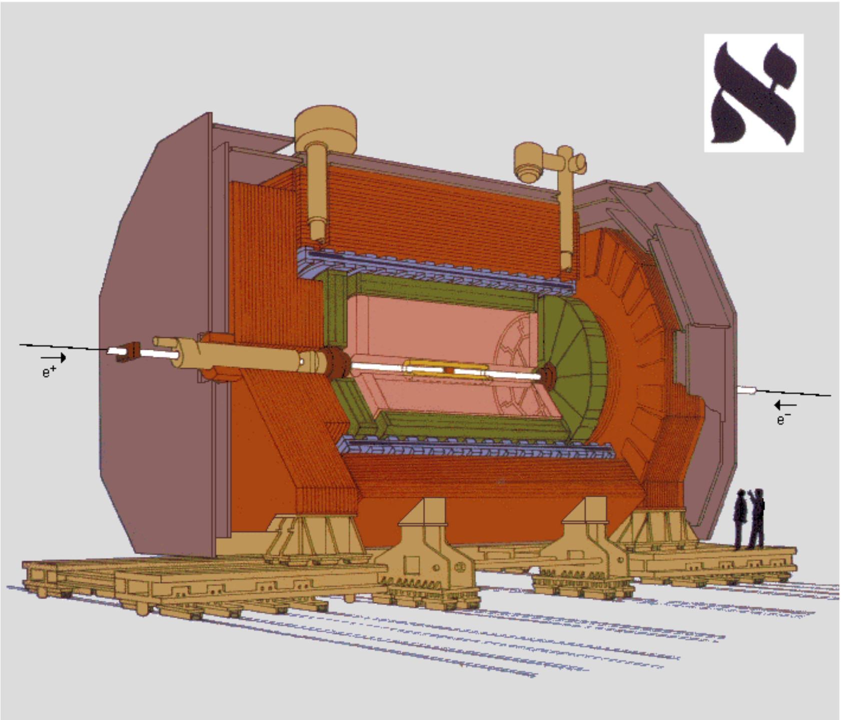
- Effect of the TGV: currents induced on the LEP beam pipe change the magnetic field
  (controlled by 16 NMR probes)

Understood after one-day strike



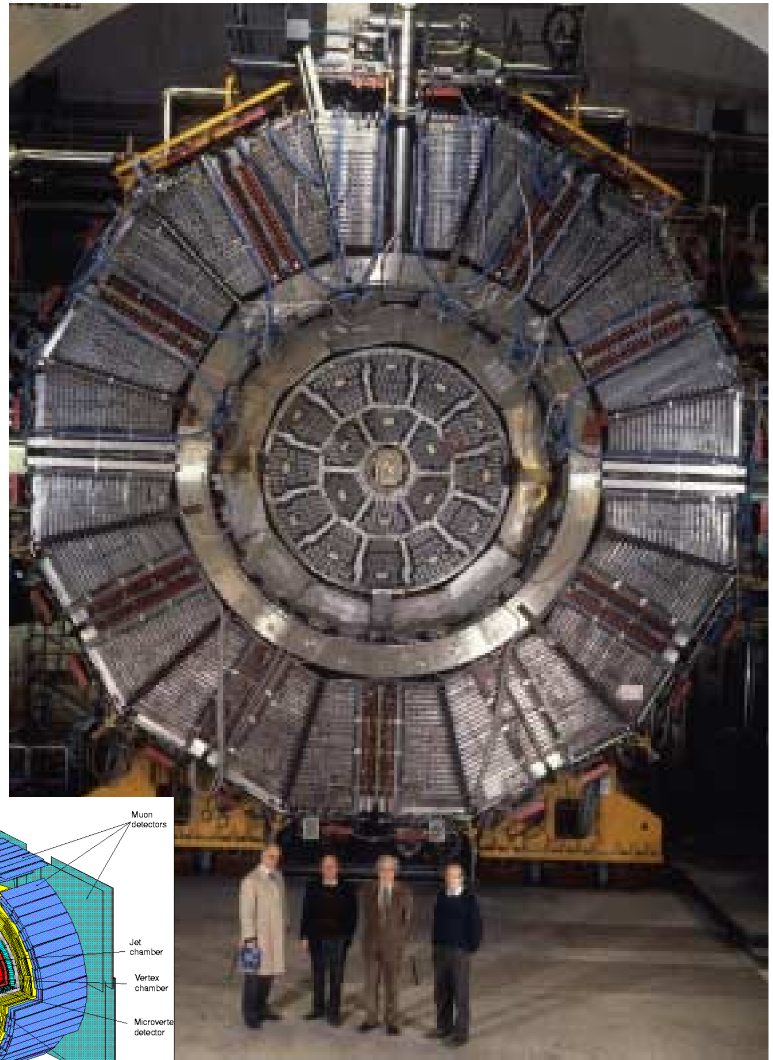
Now: $\Delta E_{beam} < 2$ MeV

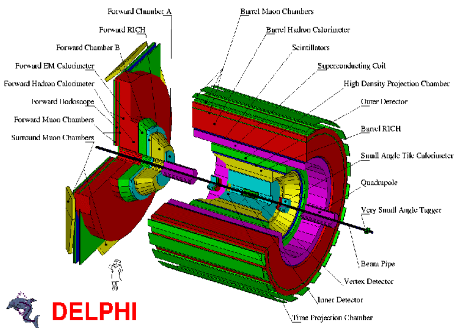
Z Lineshape: Final State Identification (I)

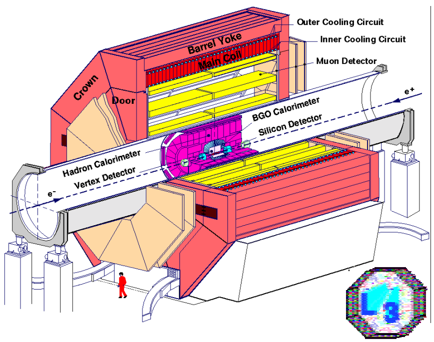


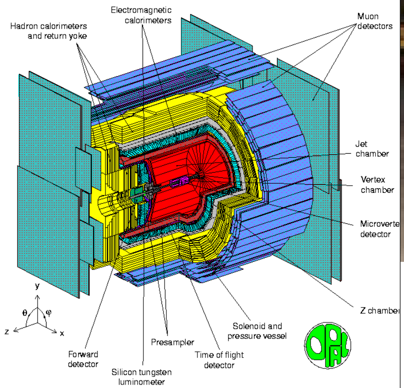
- Vertex Detector
- Inner Tracking Chamber
- Time Projection Chamber
- Electromagnetic Calorimeter
- Superconducting Magnet Coil
- Hadron Calorimeter
- Muon Chambers
- Luminosity Monitors

The ALEPH Detector

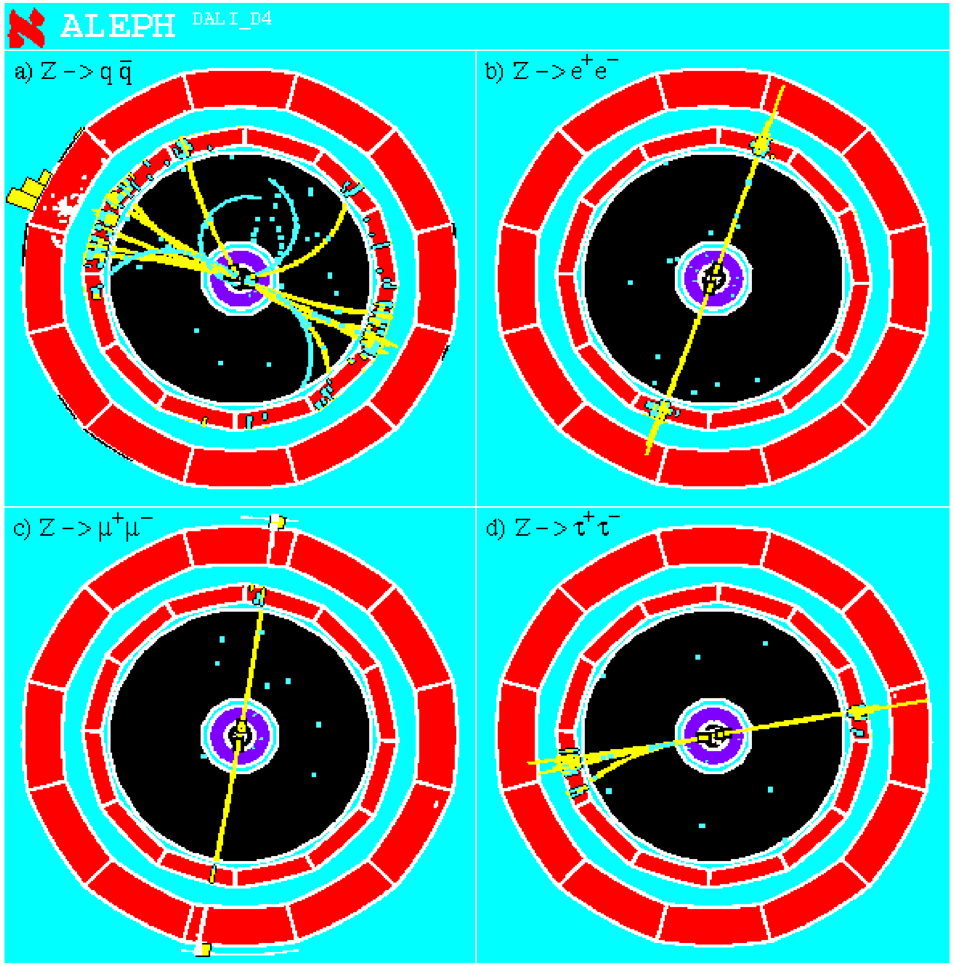


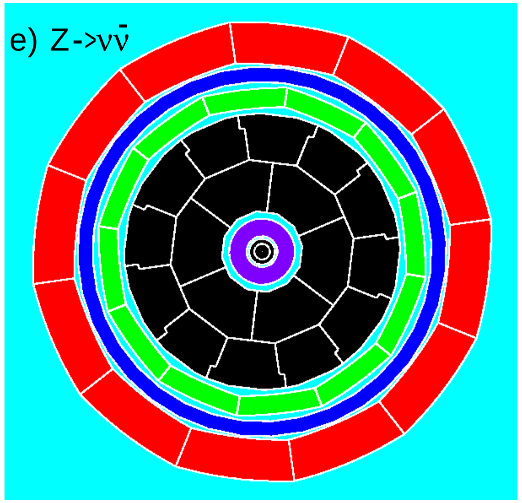






Z Lineshape: Final State Identification (II)





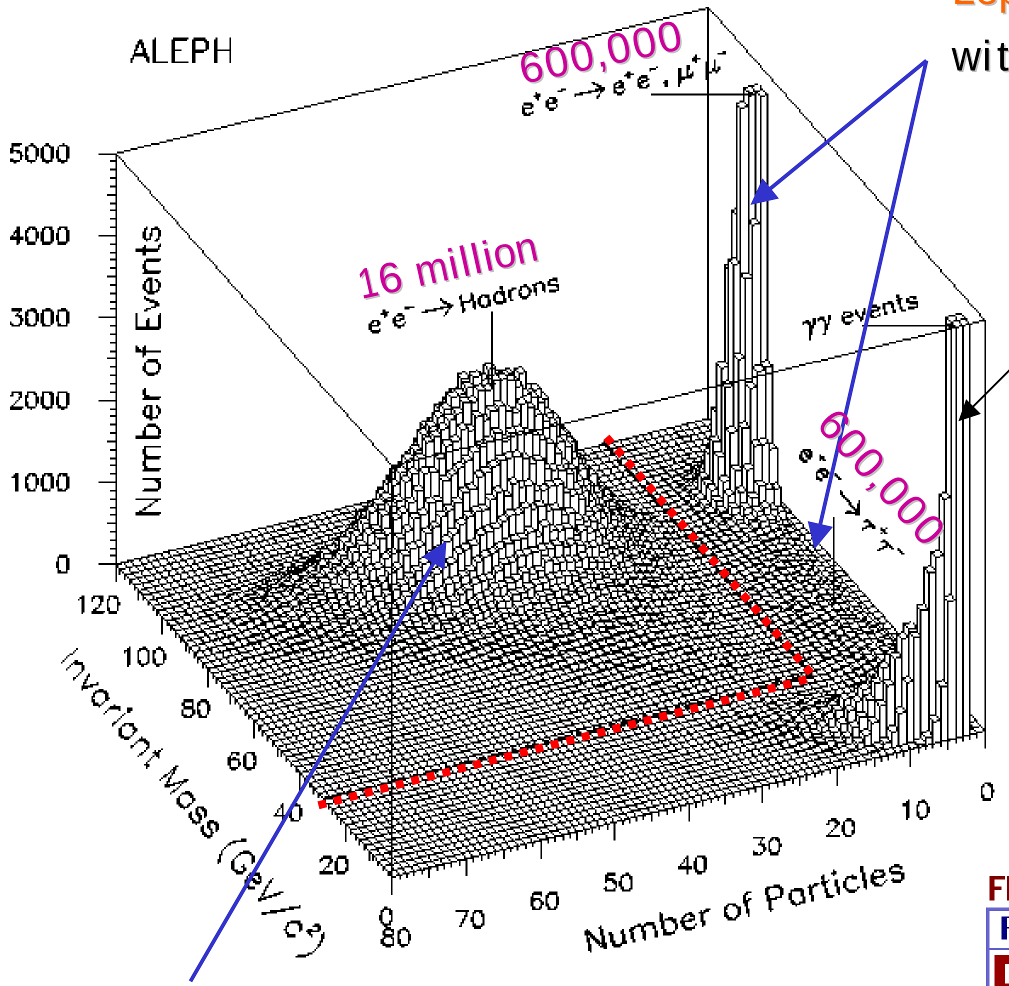
- $Z \rightarrow \nu\bar{\nu}$: Not detectable.

- $Z \rightarrow \tau^+\tau^-$: Two low multiplicity jets + missing energy carried by the decay neutrinos

Channel	Partial Width	Branching Ratio
Hadrons	1.739 GeV	70%
Neutrinos	0.497 GeV	20%
Leptons	0.250 GeV	10%

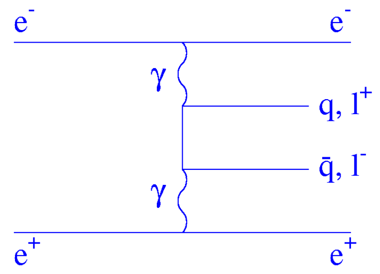
- $Z \rightarrow q\bar{q}$: Two jets, large particle multiplicity.
- $Z \rightarrow e^+e^-, \mu^+\mu^-$: Two charged particles (e or μ.)

Z Lineshape: Final State Identification (III)



Leptonic decays: Low multiplicity, with (τ) or without (e, μ) missing energy

$\gamma\gamma$ Collisions: Low multiplicity, Low mass



Selections with

- ❑ High Efficiency;
- ❑ High Purity;

Hadronic decays: High multiplicity High mass

Count events : Easy?

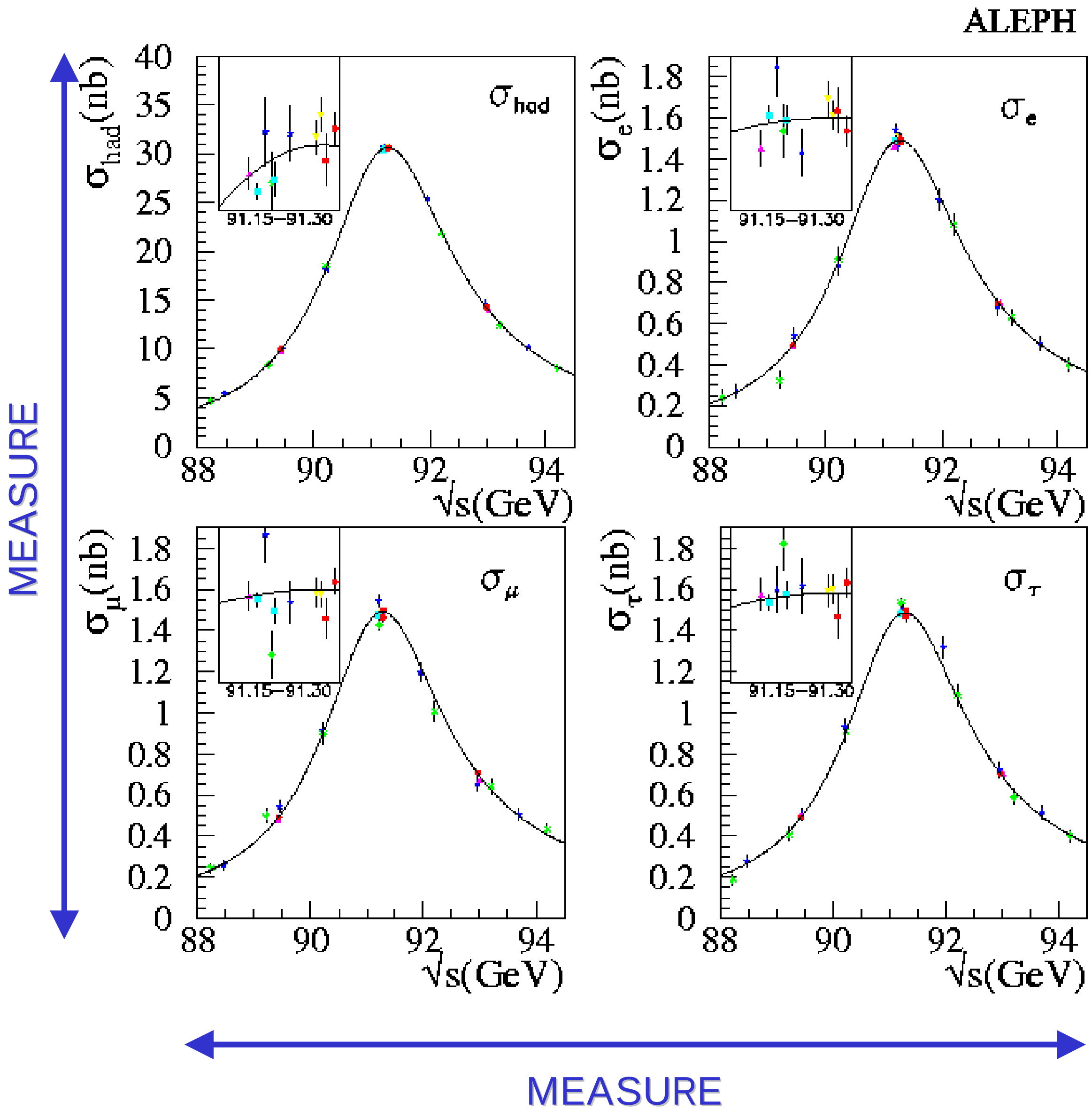
FLORIDA VOTE COUNT TOTALS Nov. 26, 2000

PRESIDENT	Nov. 7	First Recount	Certified
R Bush	2,909,176	2,911,872	2,912,790
D Gore	2,907,451	2,910,942	2,912,253
Bush Lead	1725	930	537

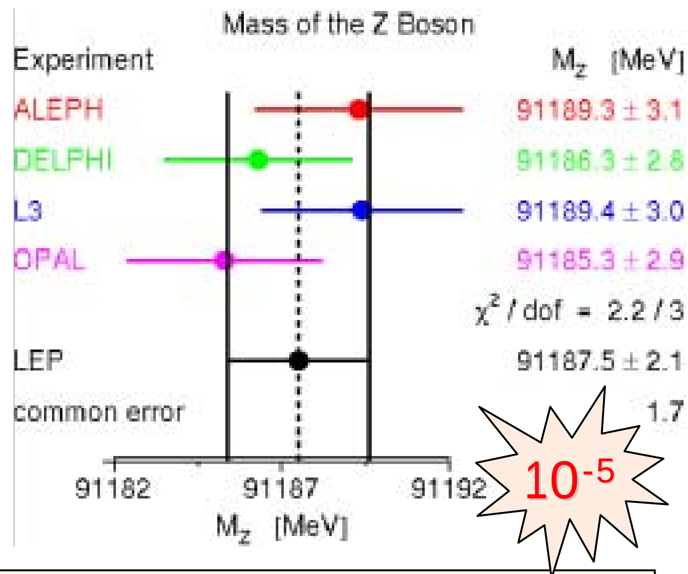
Source: State of Florida Systematic Uncertainty ~ 0.1%

25 electoral votes at stake

Z Lineshape: Results (I)

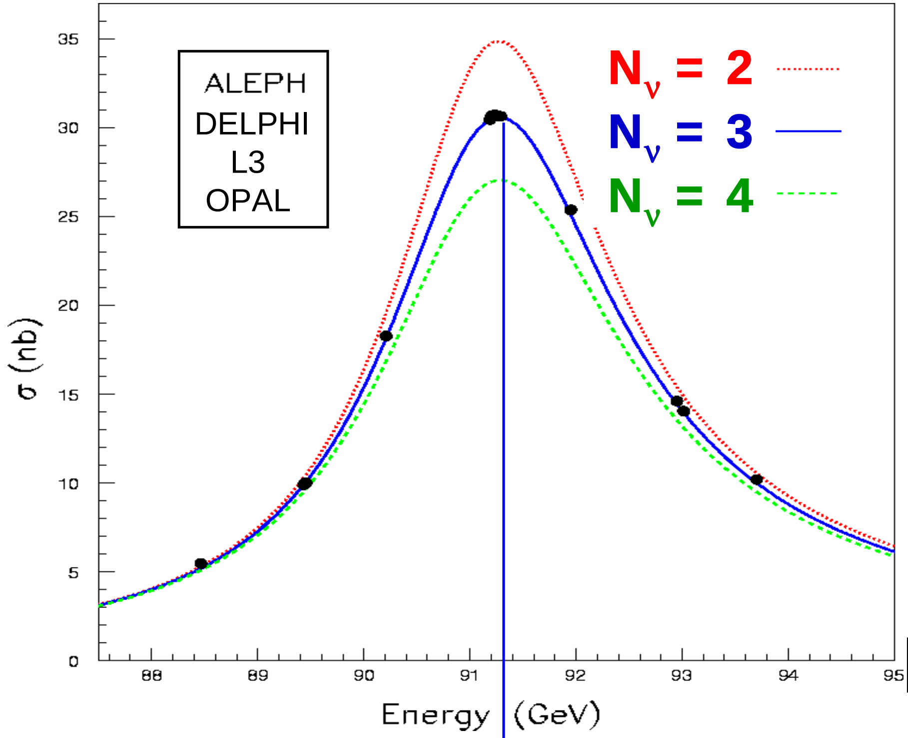


- $\sqrt{s}$ varied from 88 to 94 GeV;
- Points are from data in both coordinates;
- Lines are from a standard model fit to the Z parameters;

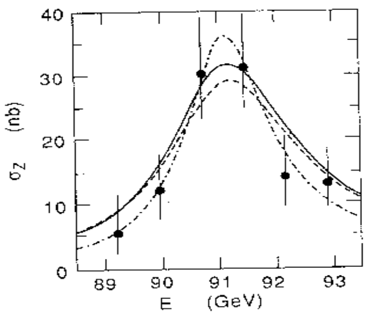


Dominant (and common) error:
LEP Beam Energy Measurement

Z Lineshape: Results (II)



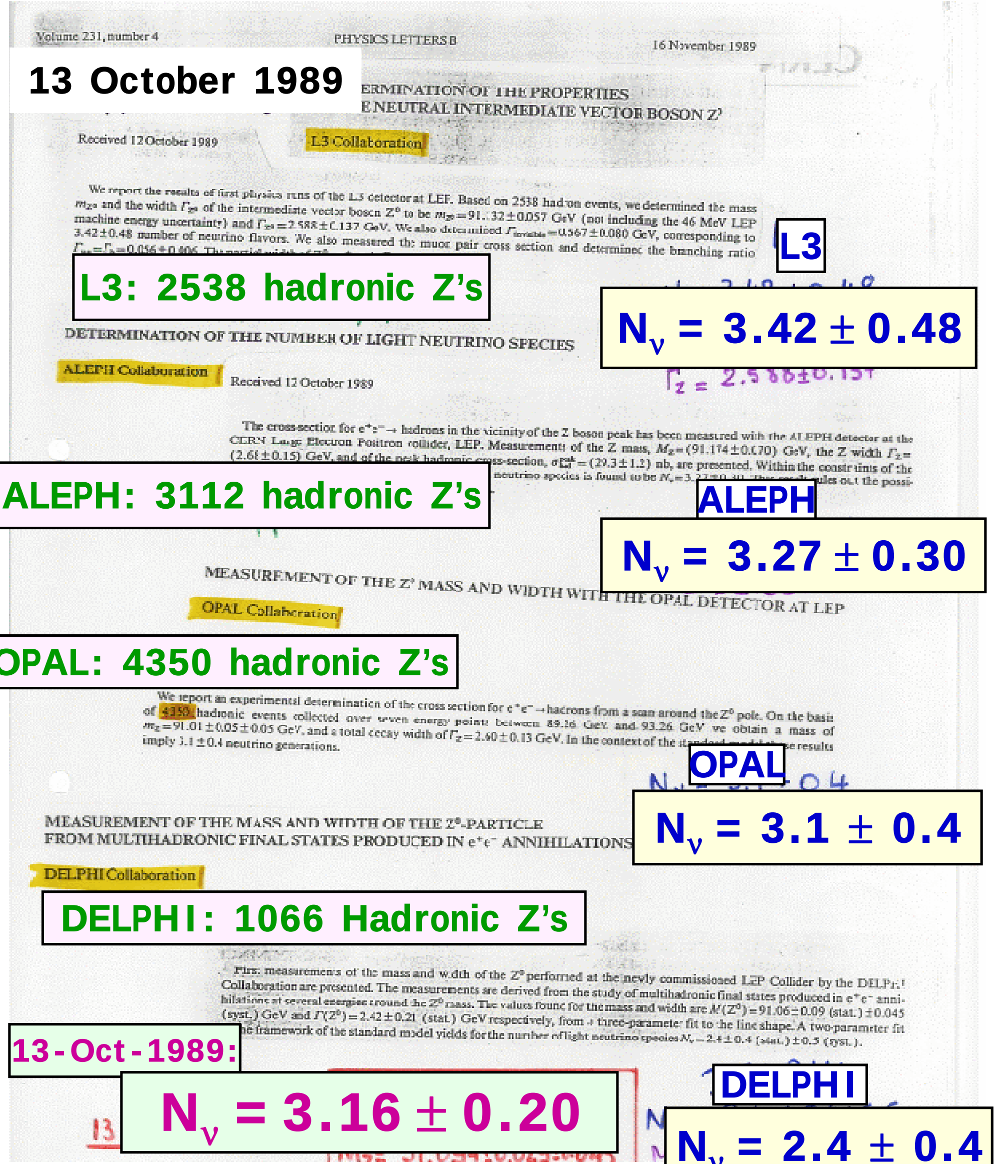
$N_\nu = 2.984 \pm 0.008$



MarkII, Aug. 1989, with 106 Z decays:

$N_\nu = 3.8 \pm 1.4$.

13 October 1989



L3: 2538 hadronic Z's

L3: $N_\nu = 3.42 \pm 0.48$

ALEPH: 3112 hadronic Z's

ALEPH: $N_\nu = 3.27 \pm 0.30$

OPAL: 4350 hadronic Z's

OPAL: $N_\nu = 3.1 \pm 0.4$

DELPHI: 1066 Hadronic Z's

DELPHI: $N_\nu = 2.4 \pm 0.4$

13-Oct-1989: $N_\nu = 3.16 \pm 0.20$

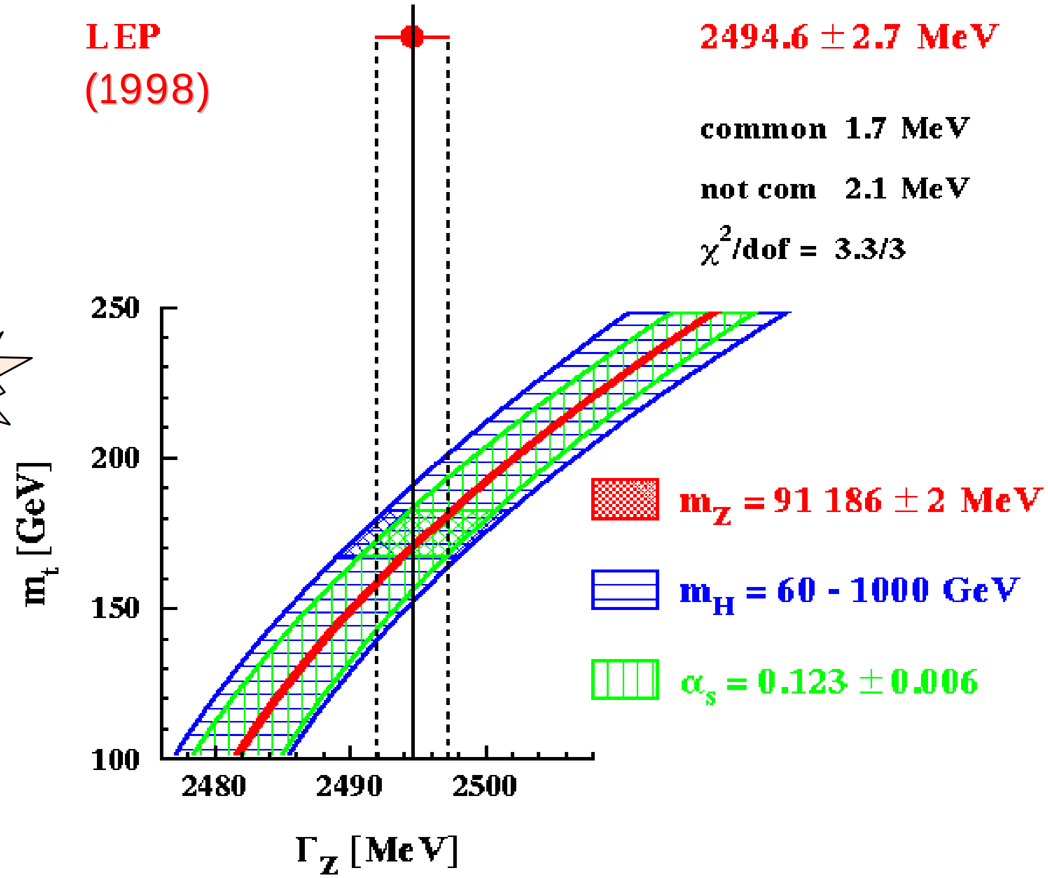
Z Lineshape: Results (III)

Obs.	Value	Error
m_Z	91187.5	2.1 MeV
Γ_Z	2495.2	2.3 MeV
σ^0	41.540	0.037 nb
R_l	20.767	0.025

10^{-3}

$\sigma^0_{had}/\sigma^0_l$

500 MeV in 1989



$\Gamma_Z \propto (1 + \Delta\rho)$

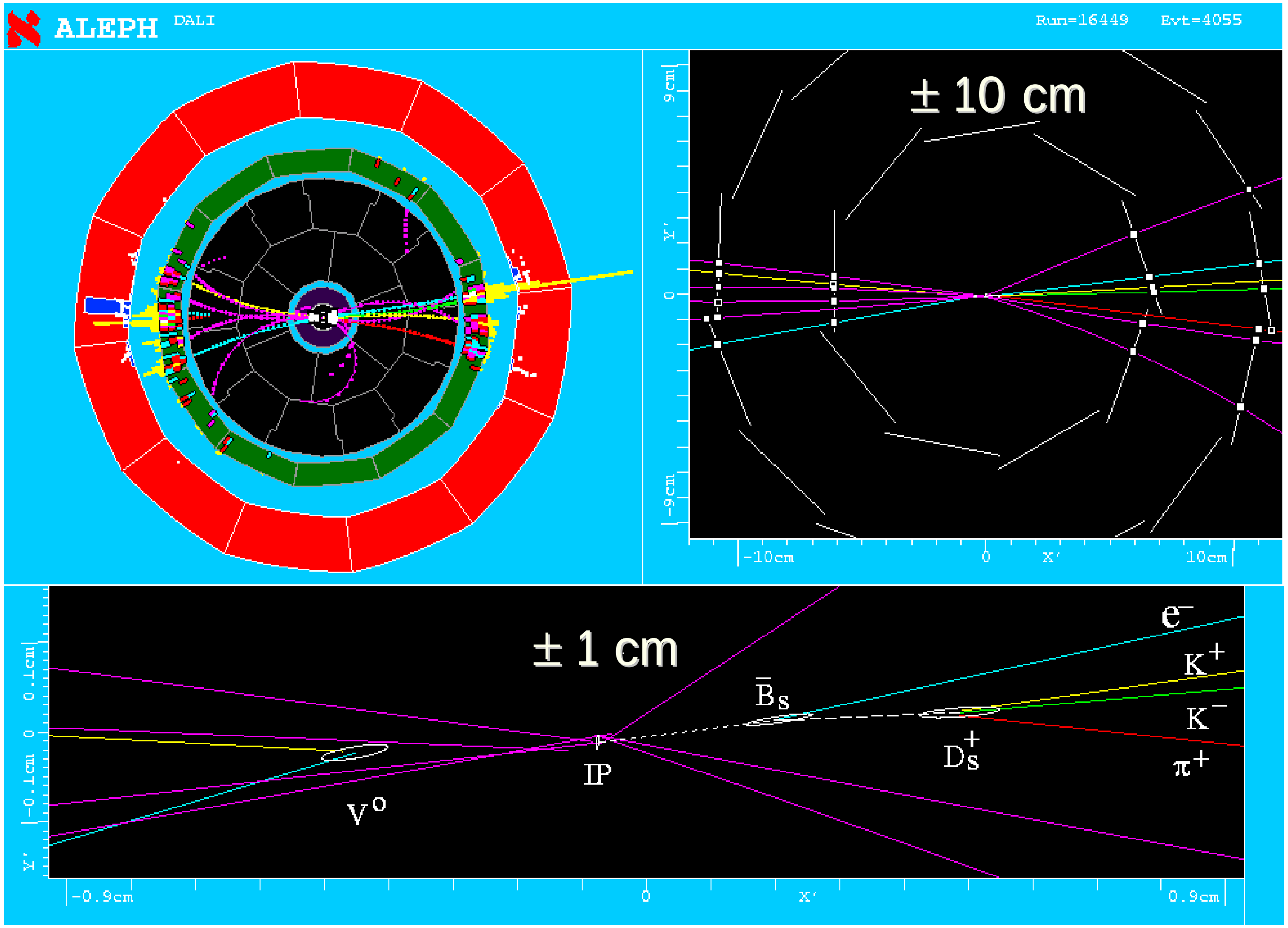
With this measurement alone:

$m_{top} \sim$ **165 ± 25 GeV/c²**

(+small sensitivity to m_H)

Heavy Flavour Rates: Identification (I)

b- and c-hadrons decay weakly towards c- and s-hadrons, with a macroscopic lifetime (1.6 ps for b's), corresponding to few mm's at LEP



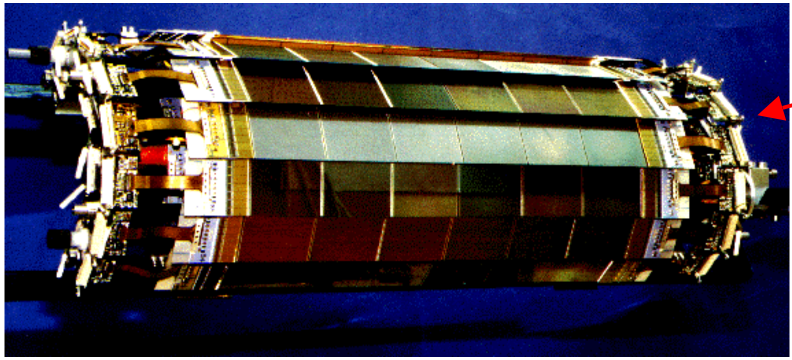
3d-vertexing determines secondary and tertiary vertices.

High resolution is crucial.

Impact parameters of reconstructed tracks allow b quarks to be tagged with very good purity.

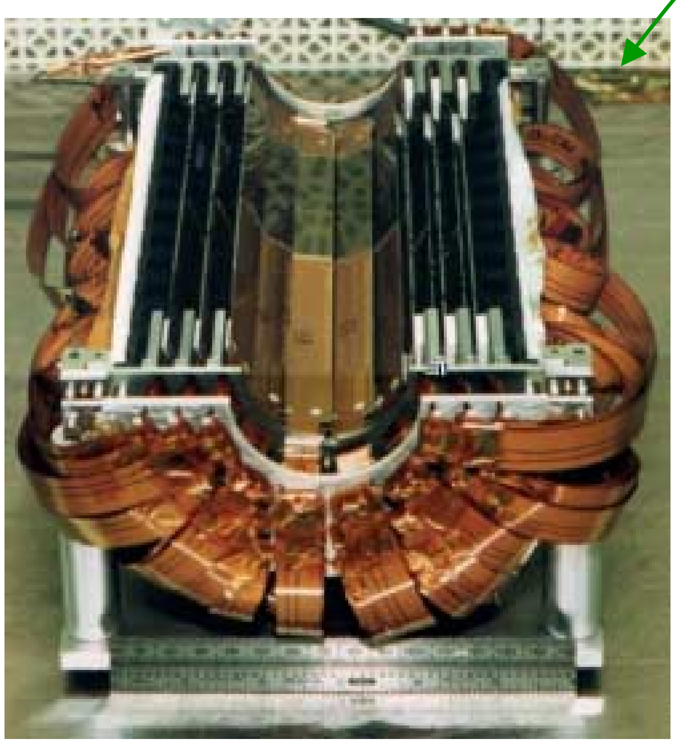
Mass of secondary vertex tracks is a very powerful discriminator of flavour (b, c, and light quarks):
$m_b \sim 5$ GeV/c^2, and
$m_c \sim 1.5$ GeV/c^2.

Heavy Flavour Rates: Identification (II)

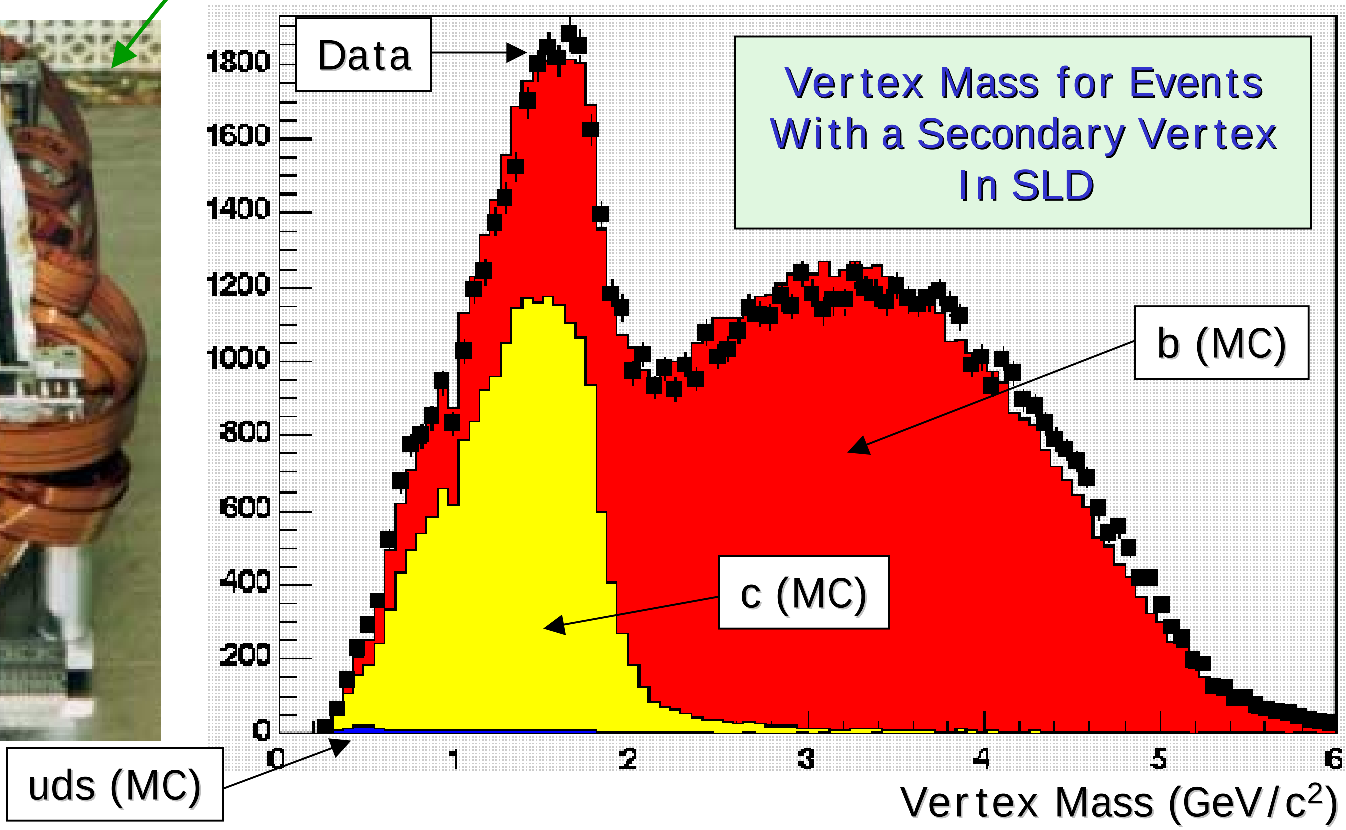


Vertex detectors (Si μ-strips, CCD's, pixels):

- At LEP: inner radius 6 cm, good resolution;
- At SLC: inner radius 2.3 cm, superior resolution.



SLD can do both b- and c-tagging with good purity.



Heavy Flavour Rates: Results

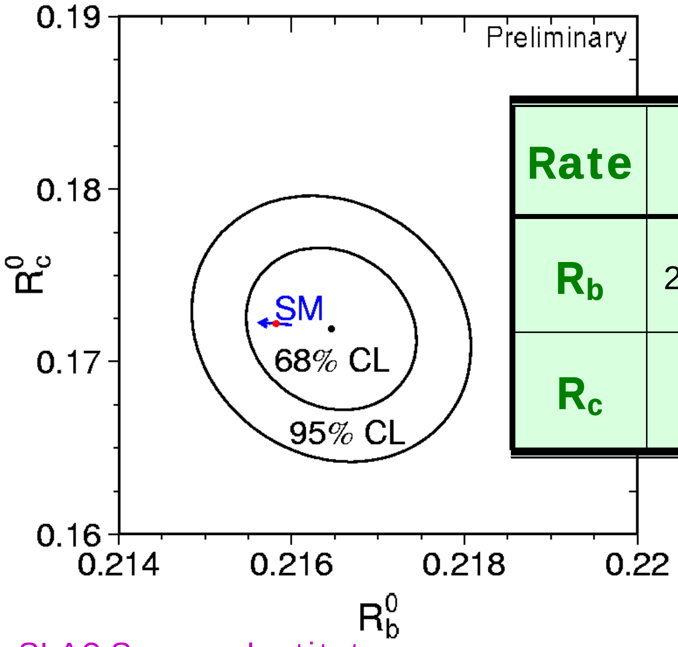
Use double-tag method to reduce uncertainties from the simulation, e.g., in bb events:

$$f_1^{\text{hemi}} = R_b \varepsilon_b + R_c \varepsilon_c + R_{uds} \varepsilon_{uds}$$

$$f_2^{\text{hemi}} = R_b \varepsilon_b^2 (1 + \rho_b) + R_c \varepsilon_c^2 + R_{uds} \varepsilon_{uds}^2$$

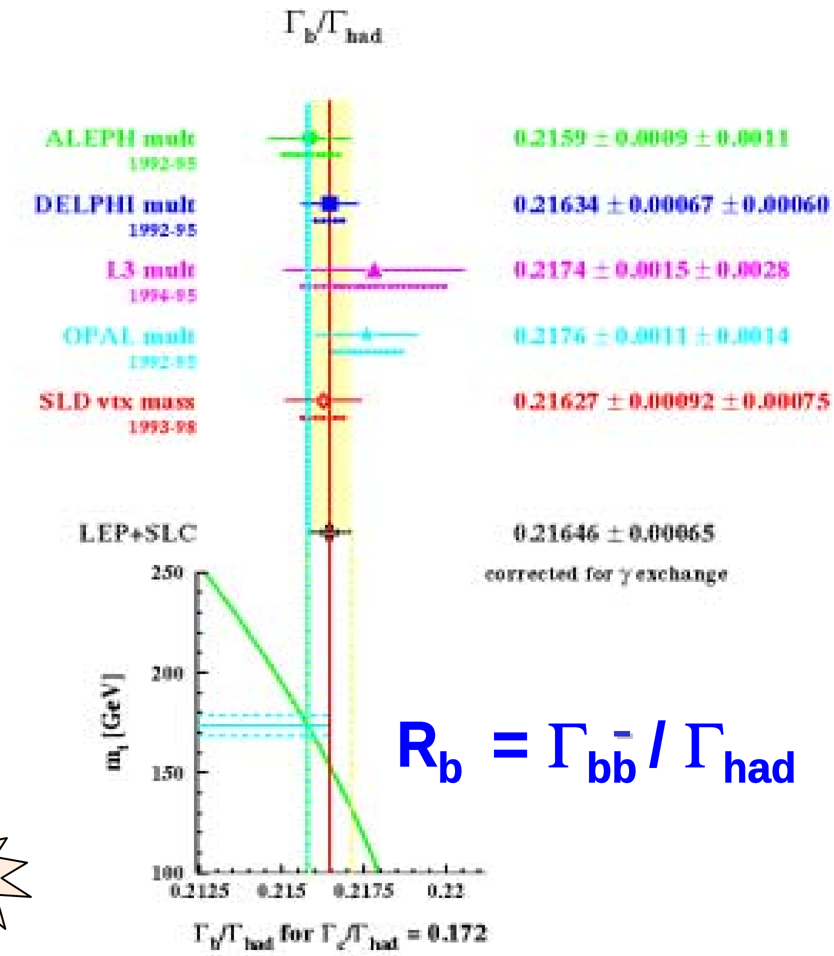
Take ε_c, ε_{uds}, and ρ_b (all small) from simulation.

Solve for ε_b and R_b !



Rate	Value	Error
R_b	21.646%	0.075%
R_c	17.19%	0.31%

$3\ 10^{-3}$



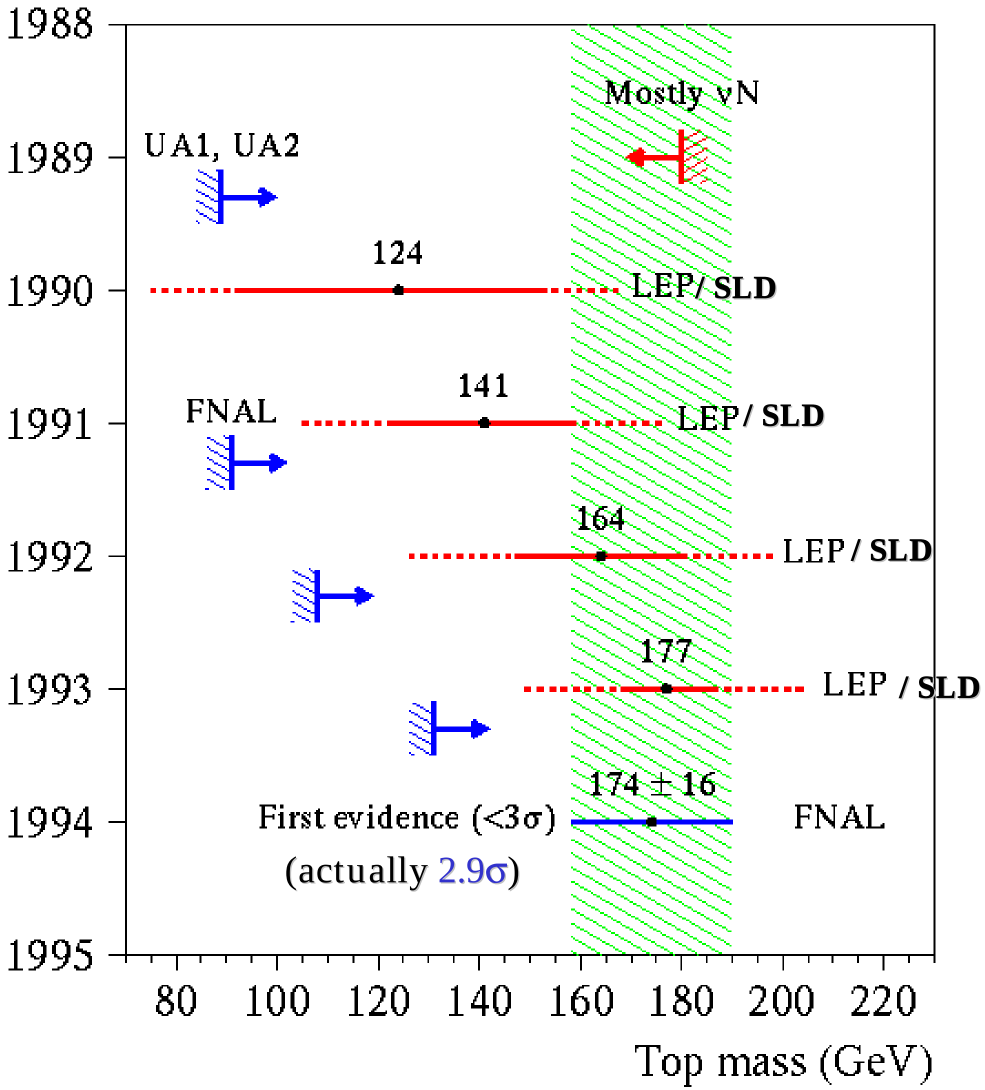
$R_b = \Gamma_{b\bar{b}} / \Gamma_{had}$

With this measurement alone:

$m_{top} \sim 150 \pm 25$ GeV/c^2

(dependence on m_H, α_s, ... cancel in the ratio)

Prediction of m_{top} from EW Measurements



A top mass of 177 GeV/c² was predicted by LEP & SLC with a precision of 10 GeV/c² in March 1994.

One month later, FNAL announced the first 3σ evidence of the top.

In 2001:

$$m_{top}^{EW} = 180.5 \pm 10.0\,\mathrm{GeV}/c^2$$

$$m_{top}^{direct} = 174.3 \pm 5.1\,\mathrm{GeV}/c^2$$

Perfect consistency between prediction and direct measurement. Allows a global fit of the SM (with m_H) to be performed.

Asymmetries: Measurement of A_{LR} at SLD (I)

$$A_{LR} = \frac{\sigma(-P_e) - \sigma(+P_e)}{\sigma(-P_e) + \sigma(+P_e)} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = A_e P_e \quad \text{with} \quad P_e = \frac{N^+ - N^-}{N^+ + N^-}$$

(e^- beam polarization)

- A_{LR} ($\propto A_e \sim$ 14% if P_e = 100%) is 10 times more sensitive to $\sin^2\theta_W$ than A_{FB}^{lept} ($\propto A_e A_l \sim$ 1-2%);
- A_{LR} is independent of the final state ($Z \to$ hadrons, $\tau^+\tau^-$, $\mu^+\mu^-$);
- A_{LR} is independent of the detector acceptance;
- Most of the theoretical corrections, uncertainties (QED, QCD, ...) cancel in the A_{LR} ratio.

Statistical & Systematic } uncertainties compete with LEP asymmetry measurements (unpolarized)

Asymmetries: Measurement of A_{LR} at SLD (II)

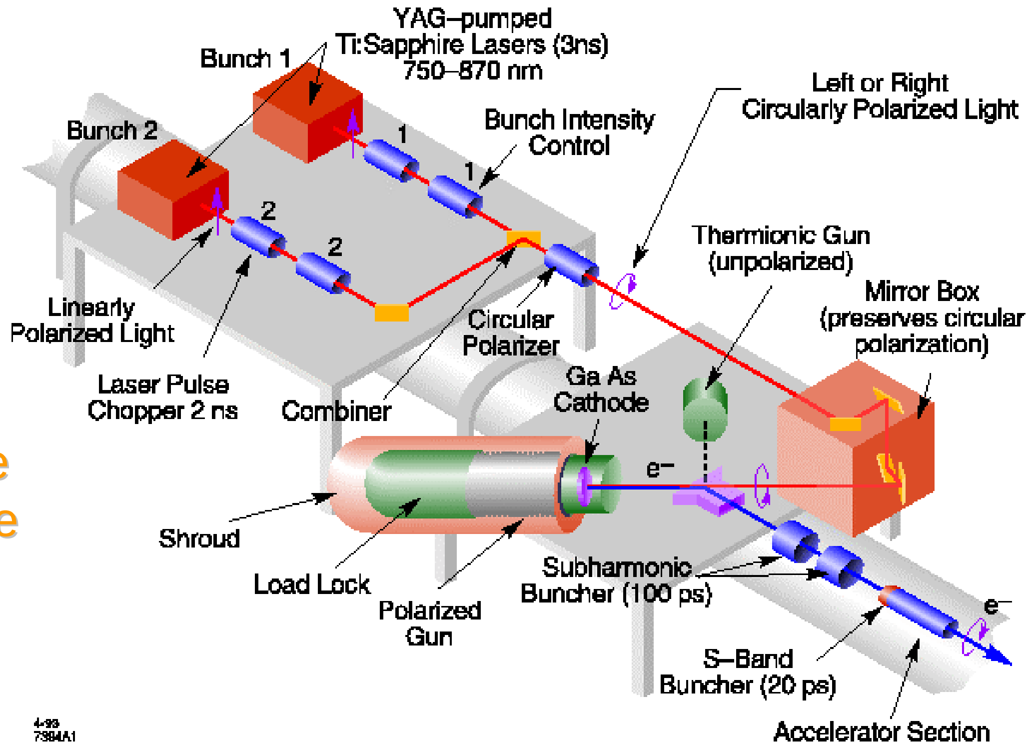
Condition # 1: Have a longitudinally ~100% polarized electron beam.

- Get longitudinally polarized e^- by illuminating a GaAs photo cathode with circularly polarized Lasers (frequency: $2 \times 60 = 120$ Hz)

- In principle, $P_e \sim 100\%$ can be reached. In practice, 80% was achieved.

- Change the sign of the polarization on a random basis to ensure that equal amount of data are taken with both signs, and that the luminosity is not tied to any periodic effects in SLC.

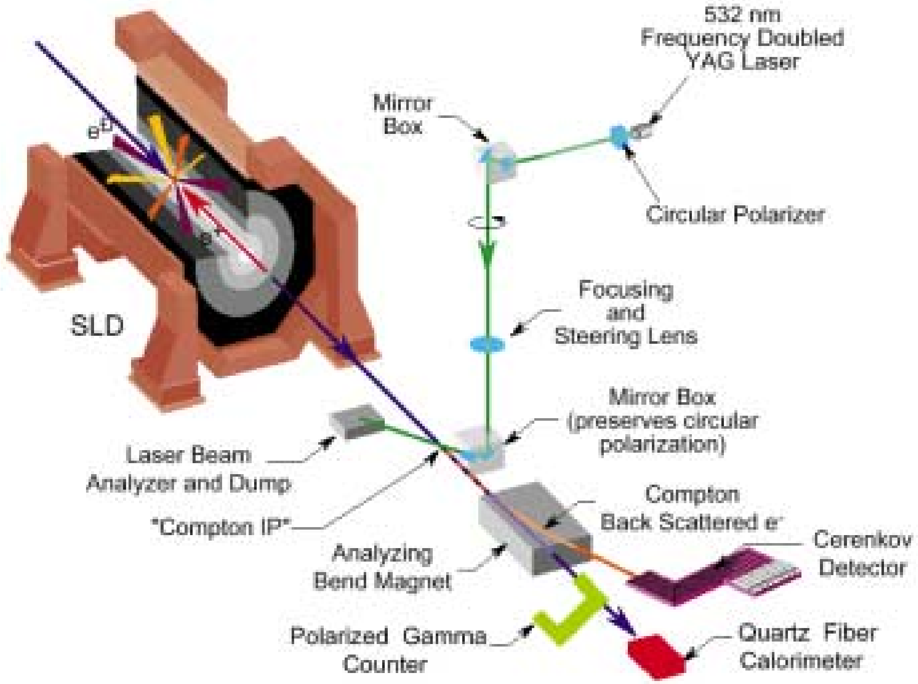
- Transport, accelerate and collide the polarized electrons, with enough care to keep the same polarization at the interaction point. SLC was designed to do so from the beginning (unlike LEP).

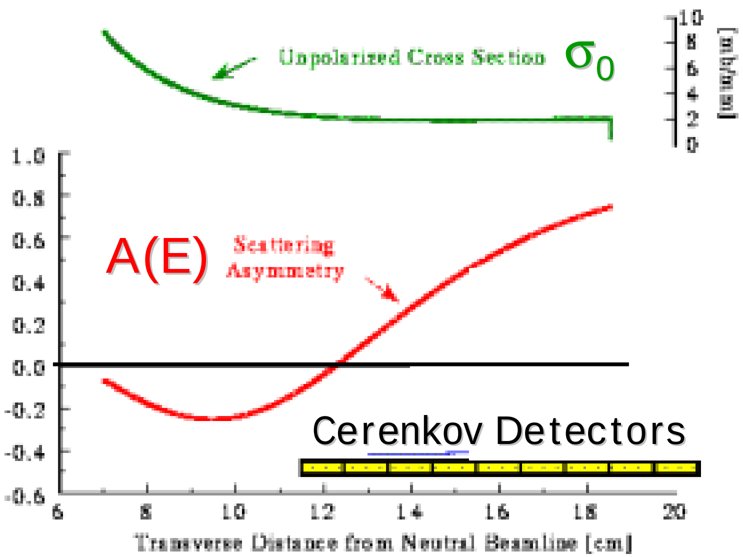


Asymmetries: Measurement of A_{LR} at SLD (III)

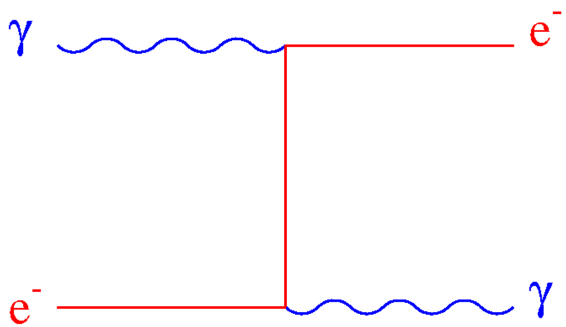
Condition # 2: Measure the e^- polarization P_e with 0.5% accuracy.

- Collide 45.6 GeV long. polarized e^- with 2.33 eV (532 nm) circularly polarized photons every 7th bunch (17 Hz);
- Detect Compton back-scattered e^- as a function of their energy after a bend magnet;
- $\sigma(E) = \sigma_0 \times [1 + A(E)\, P_e\, P_\gamma]$





σ_0 and $A(E)$ are theoretically well known (pure QED process)



Asymmetries: Measurement of A_{LR} at SLD (IV)

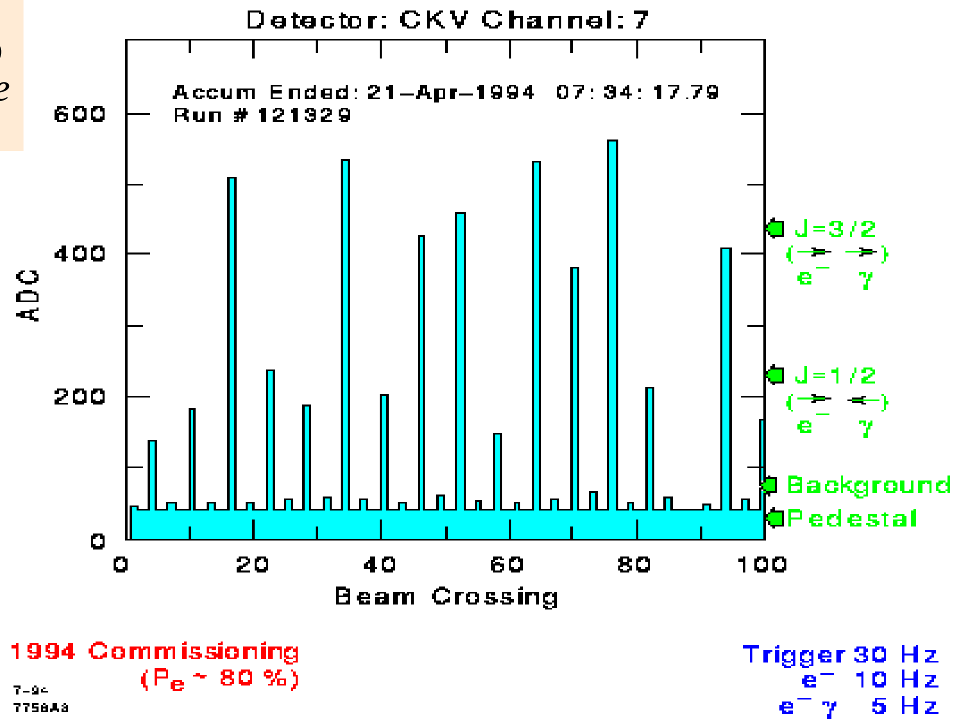
- Reverse on a random basis the sign of the photon polarization P_γ
  (close to 100%, optically measured with filters);

- Count the number of e^- detected in each of the Cerenkov channels
  (about a hundred electrons per channel at each beam crossing)

- Deduce the e^- beam polarization from the asymmetry

$$\frac{N^{\rightarrow} - N^{\leftarrow}}{N^{\rightarrow} + N^{\leftarrow} - 2N^{\text{offset}}} = A(E)P_\gamma P_e$$

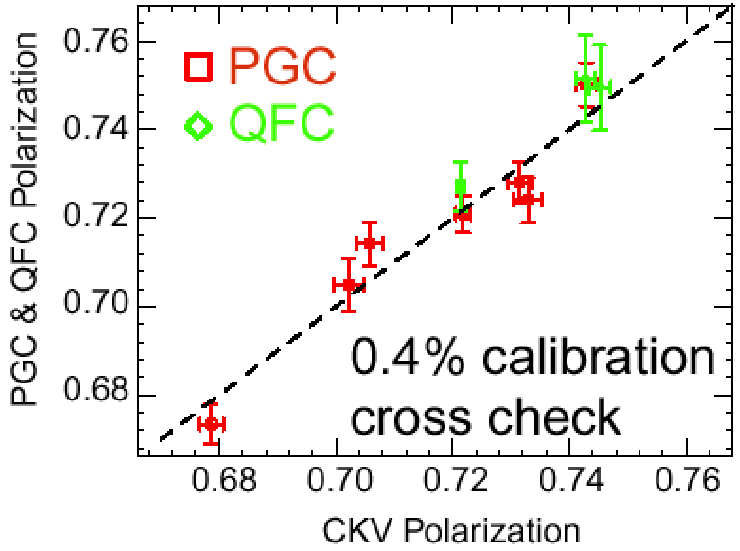
Uncertainty	δP/P
Laser Polarization	0.1%
Analyzing Power	0.4%
Linearity	0.2%
Electronic Noise	0.2%
TOTAL	0.5%



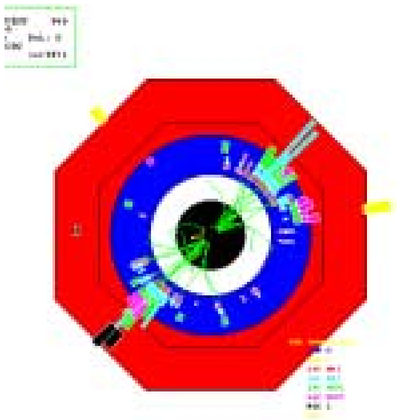
Asymmetries: Measurement of A_{LR} at SLD (V)

Cross-checks:

- Count Compton-scattered gammas at the kin. threshold with two additional calorimeters. Agree with the main measurement to 0.4%.
- Measure the positron polarization to be 0.0% with an accuracy better than 0.1%.



Condition # 3: Count events in SLD



$$A_{LR} = \frac{N_L - N_R}{N_L + N_R} = A_e P_e$$

e.g., in 1997-98:

o N_L = 183,355; N_R = 148,259

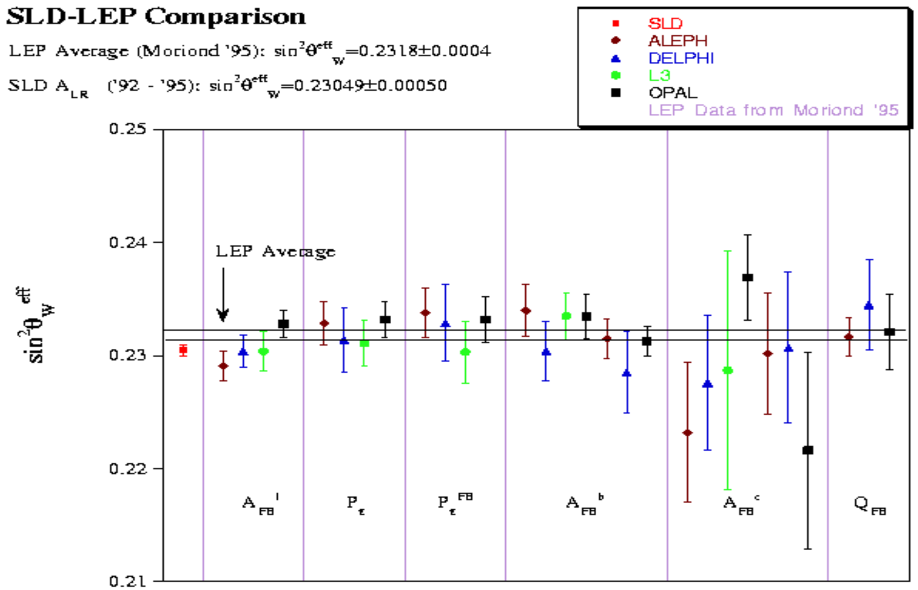
o P_e = 72.92%

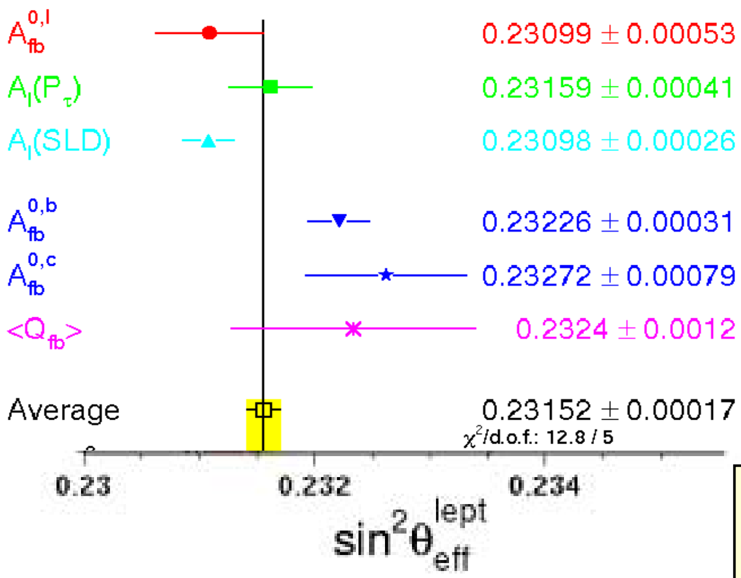
$\Rightarrow A_e = 0.1491 \pm 0.0024$ (stat.) ± 0.0010 (syst.)

Complete data set:

$$A_e = 0.15138 \pm 0.00216$$
$$\sin^2 \vartheta_W^{\text{eff}} = 0.23097 \pm 0.00027$$

Asymmetries: Results for $\sin^2\theta_W^{eff}$





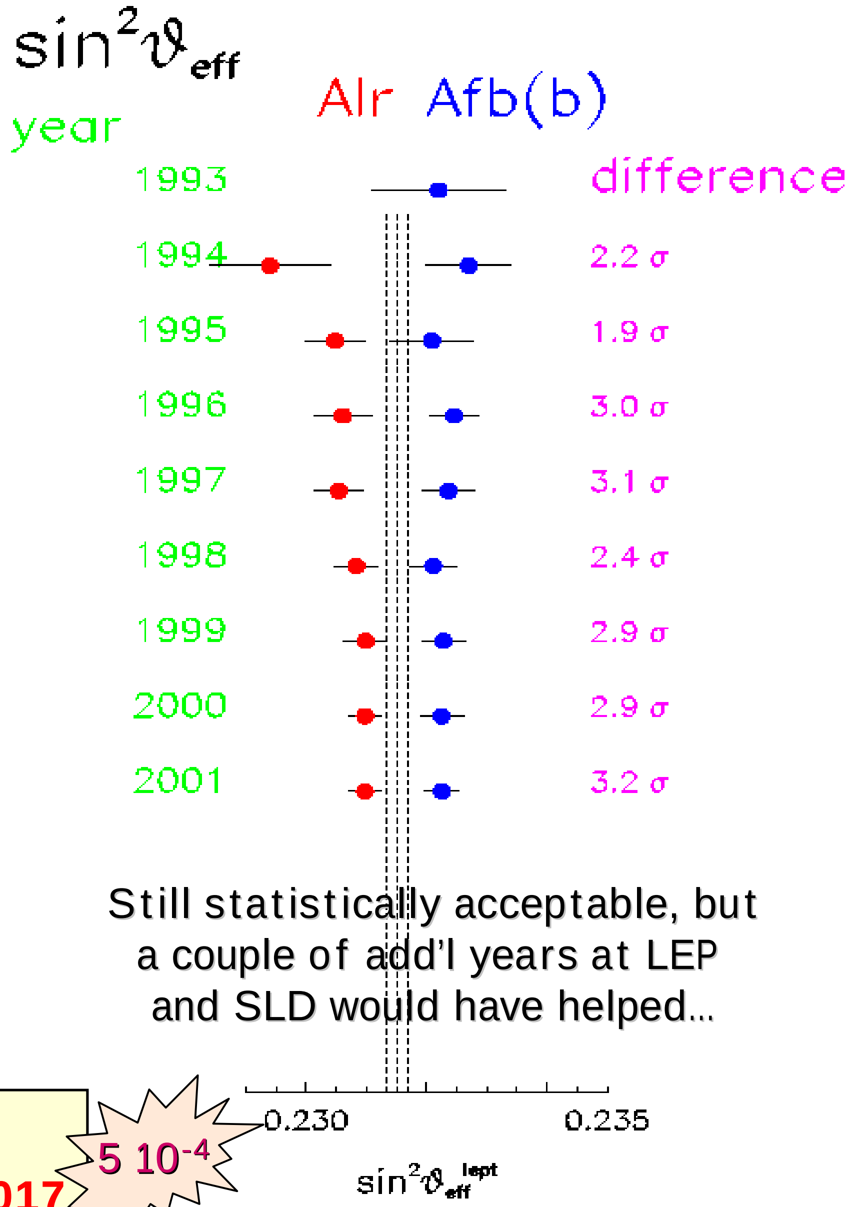
Leptons:
0.2310±0.0002

???

Quarks:
0.2323±0.0003

ALL:
0.23152±0.00017

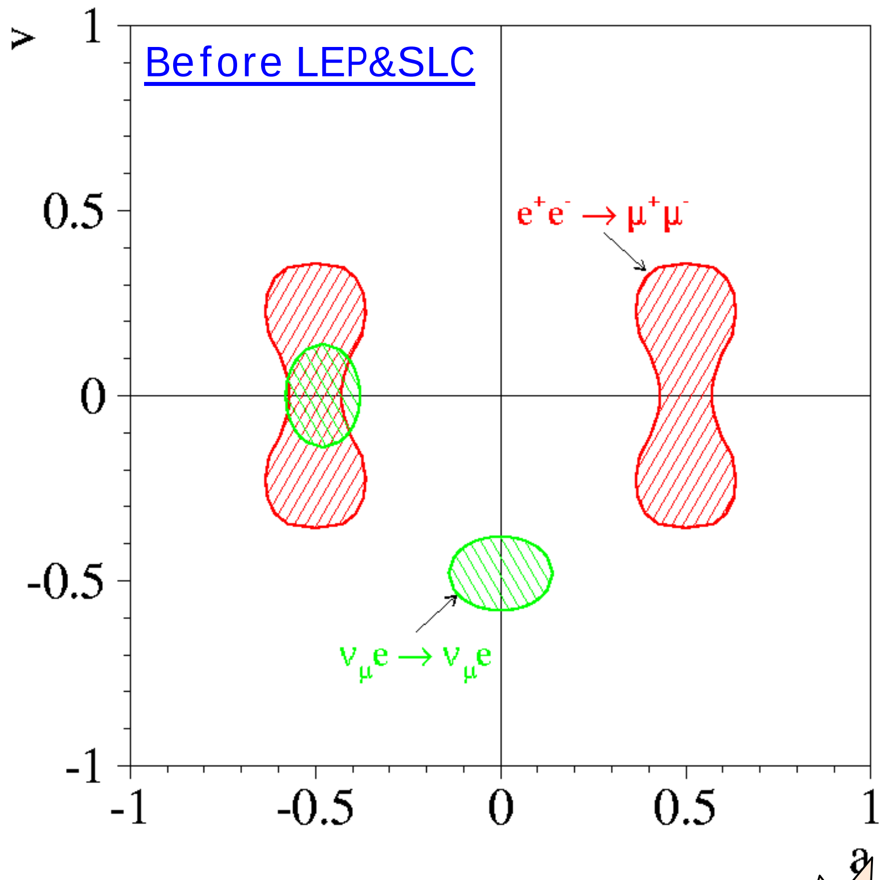
$5\ 10^{-4}$

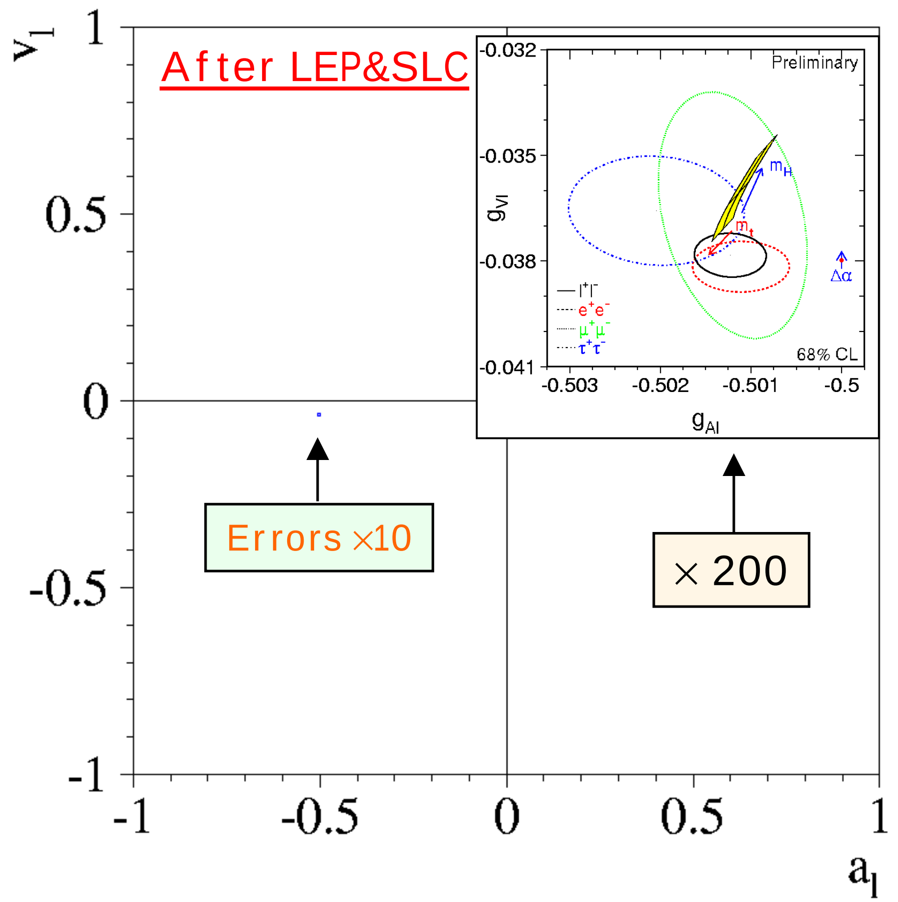


Still statistically acceptable, but a couple of add'l years at LEP and SLD would have helped...

Asymmetries: Results for a_l and v_l

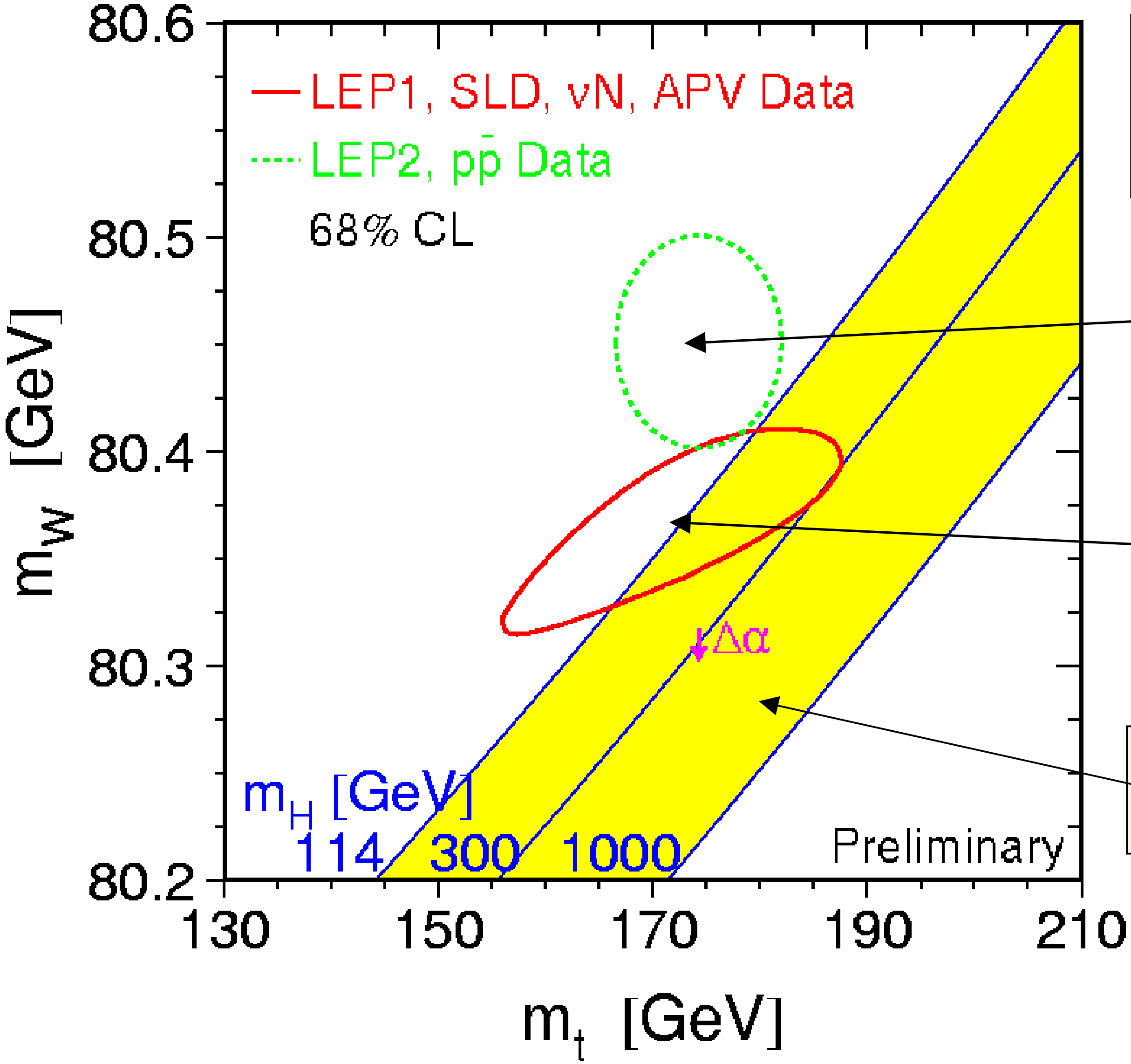
Axial and vector couplings (a_l, v_l) from A_{LR} (SLC) and $Z \to l^+l^-$ (LEP)





Precision on $\sin^2\theta_W$: 5 10^{-4}, adequate to become sensitive to m_H.

Asymmetries: Prediction of m_W



Predict m_W in the SM:

$$m_W^2 = m_Z^2(1 + \Delta\rho)\cos^2\vartheta_W^{eff}$$

Direct Measurements*

Precision Measurements

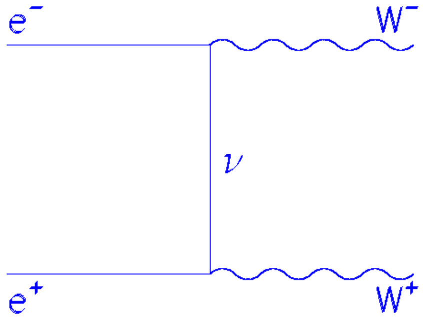
m_H dependence in the SM through quantum corrections

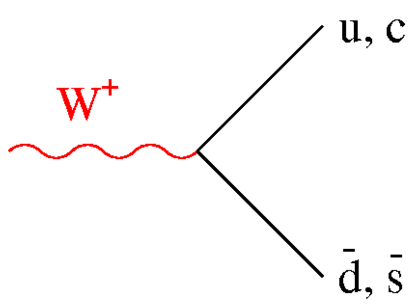
(see later)

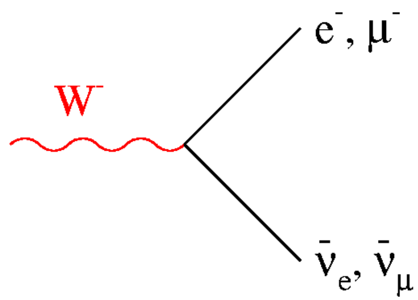
* Coming now for m_W at LEP;
See Y.-K. Kim lecture for m_{top} and m_W at the Tevatron.

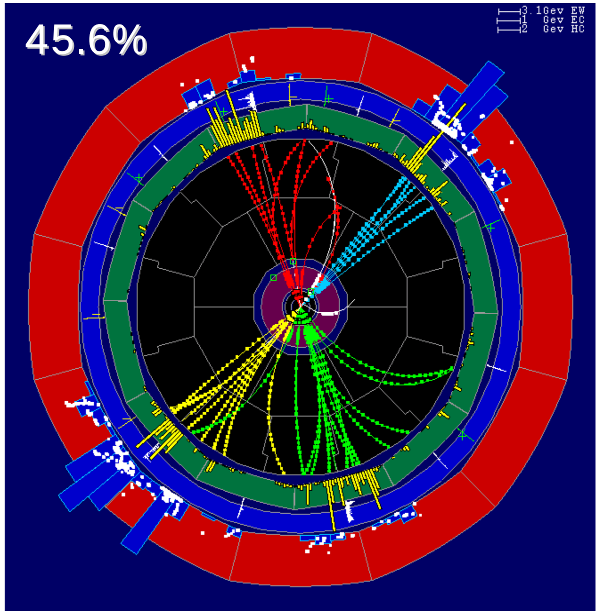
W mass at LEP 2: Production and Decay

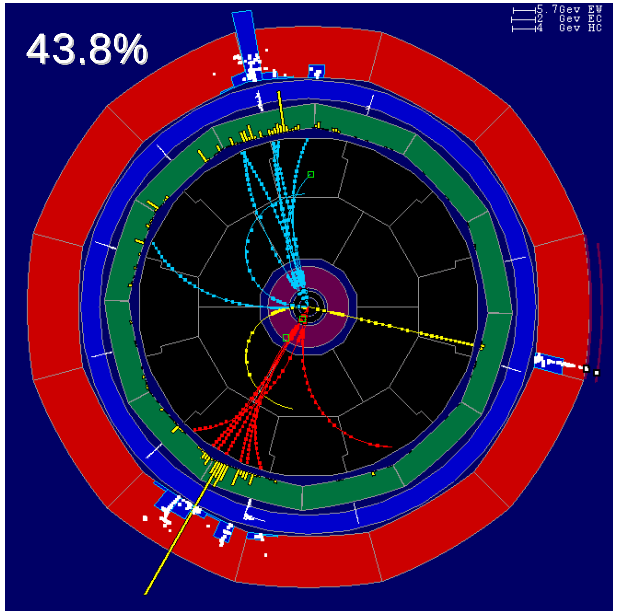
$\sqrt{s} \geq 2m_W$

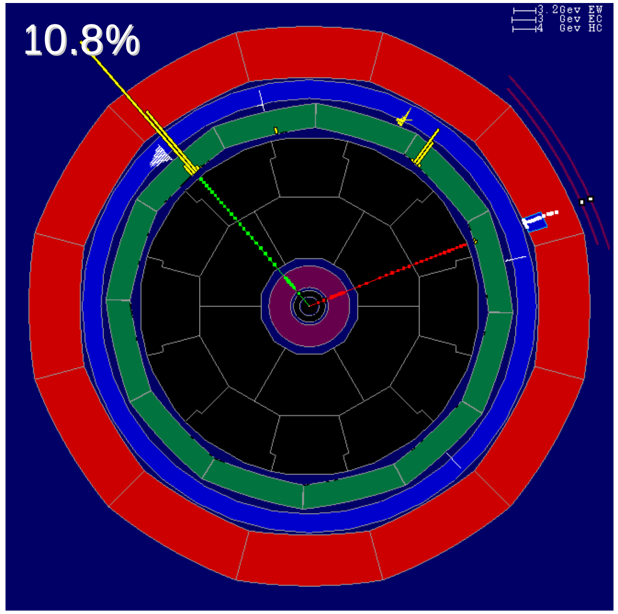










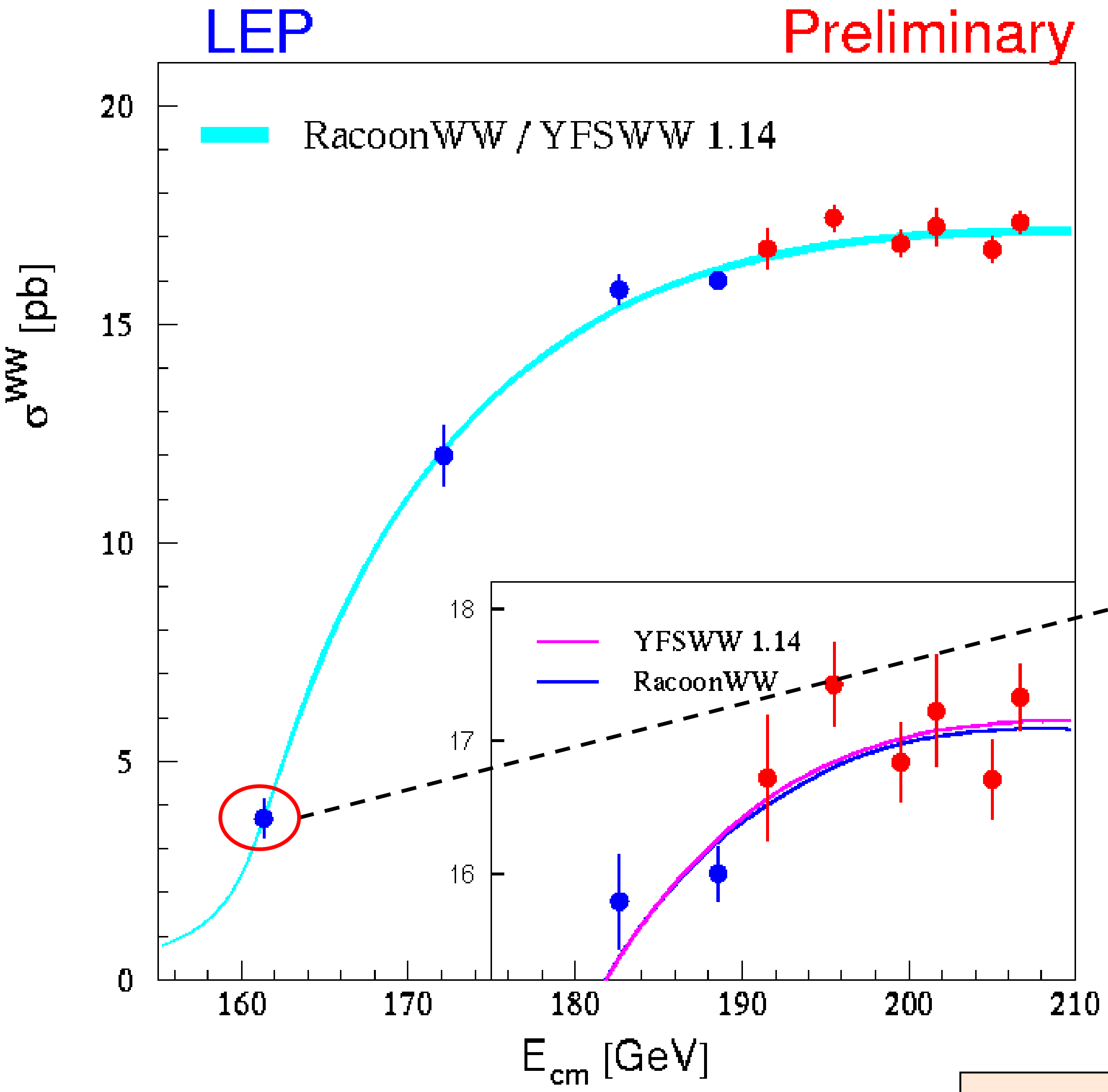


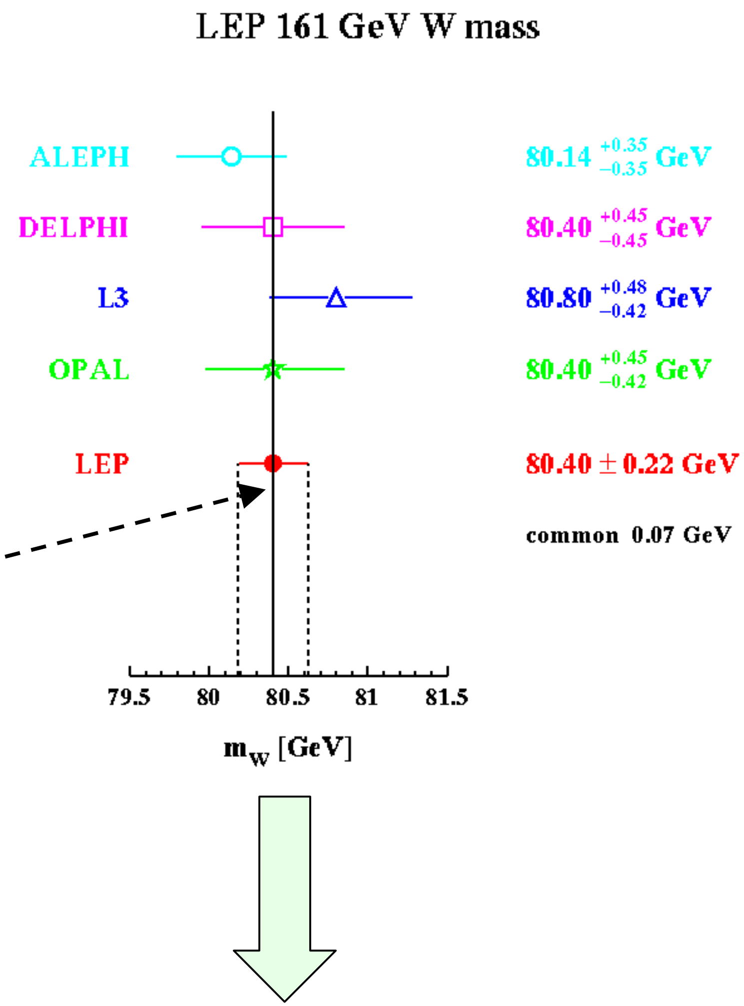
$W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$:
Four well separated jets.

$W^+W^- \rightarrow q_1\bar{q}_2l\bar{\nu}$:
Two hadronic jets,
One lepton, missing energy.

$W^+W^- \rightarrow l_1\nu_1l_2\bar{\nu}_2$:
Two leptons, missing energy

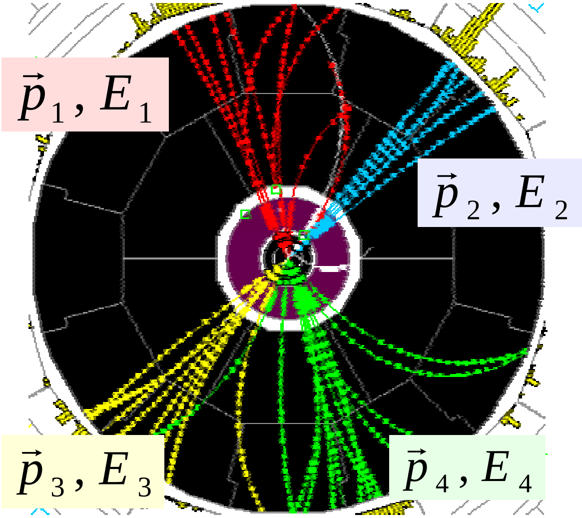
W mass at LEP 2: Threshold cross section



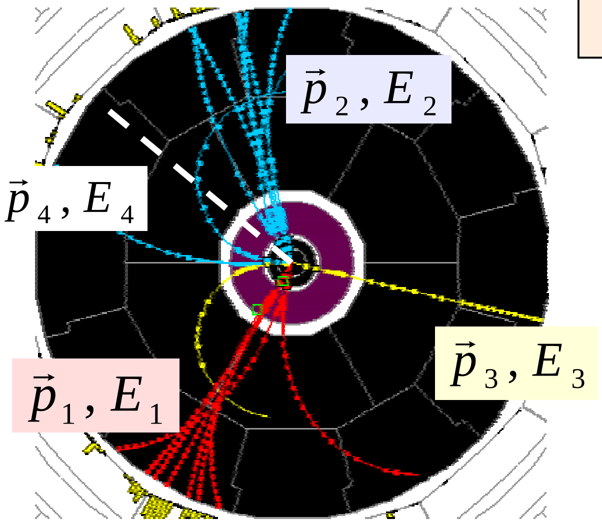


m_W (thresh.) = (80.40 ± 0.22) GeV/c^2

W mass at LEP 2: Direct measurement (I)



0 unknowns,
5C fit

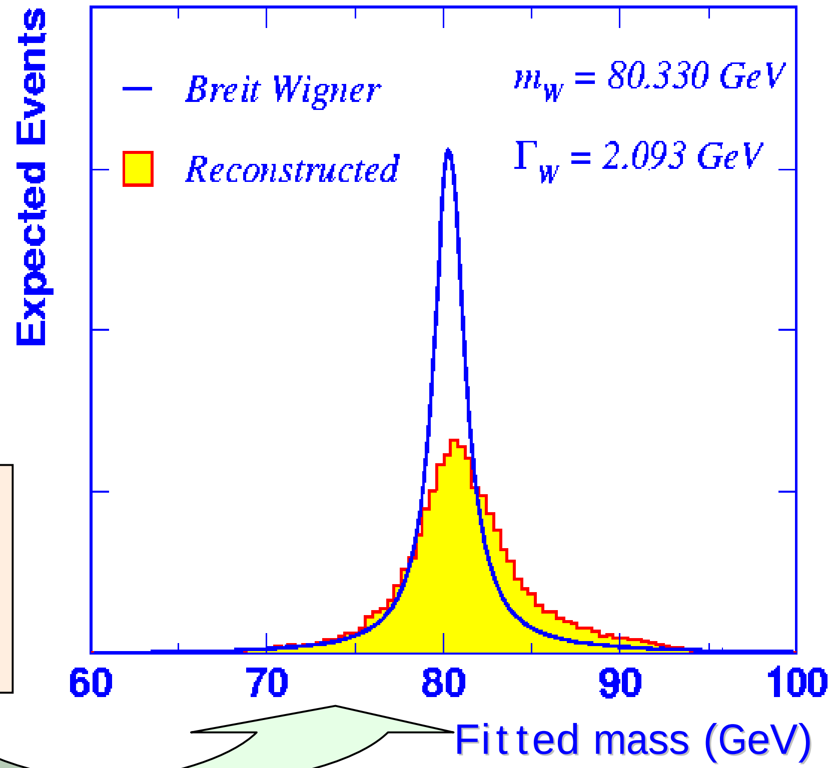


3 unknowns,
2C fit

5 Constraints:

$$\sum_{i=1}^{4} E_i = \sqrt{s}, \quad \sum_{i=1}^{4} \vec{p}_i = \vec{0},$$

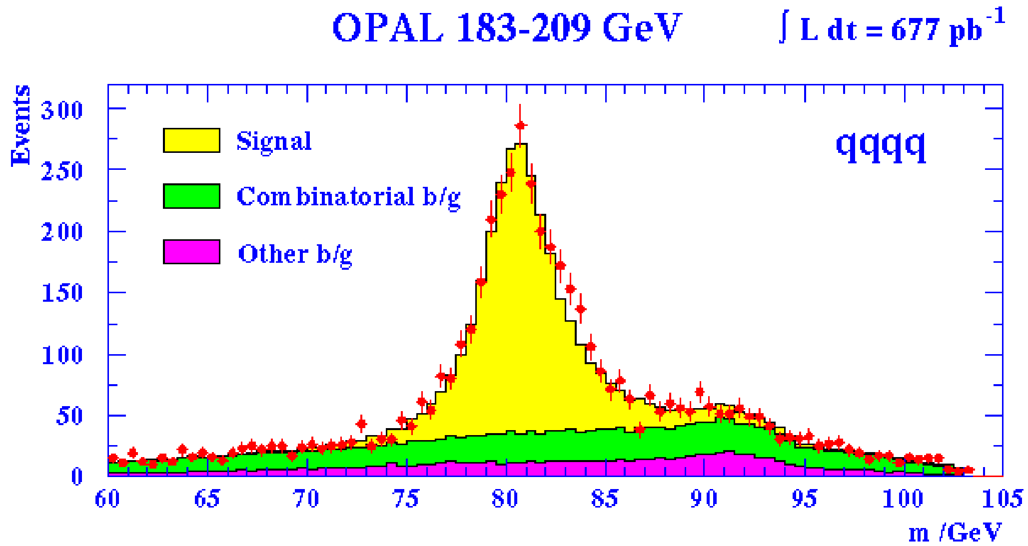
$$m_W^+ = m_W^-$$

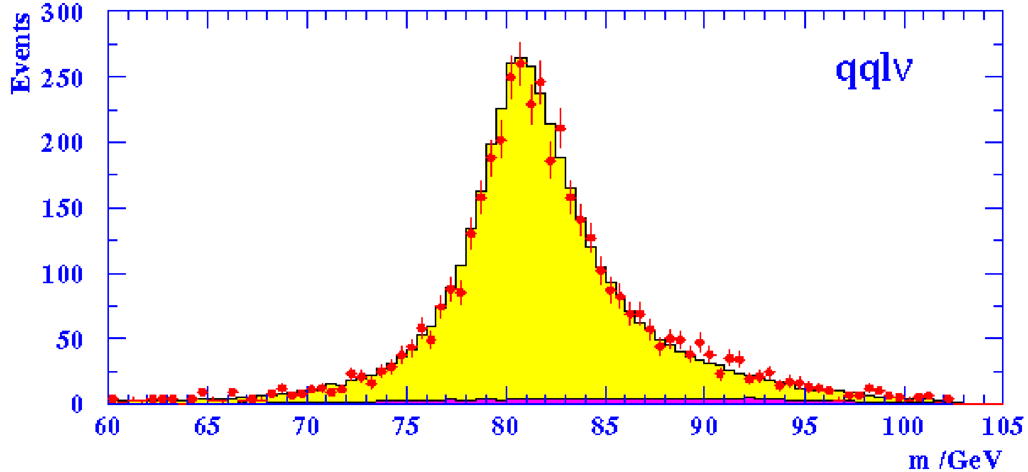


- Initial State Radiation;
  (change the effective beam energy)
- Detector Resolution;
  (change the jet directions)
- Other four-fermion diagrams
  (create non-Breit-Wigner bkgds)

W mass at LEP 2: Direct measurement (II)

⇒ Mostly rely on simulated mass distributions to determine m_W





10,000 W pairs per experiment

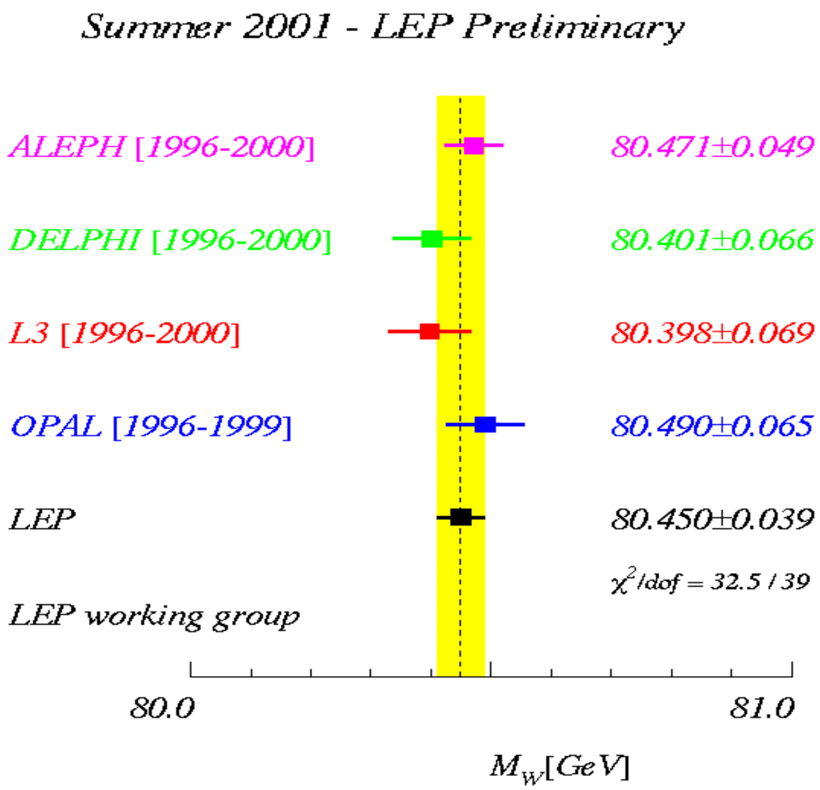
LEP Combination:

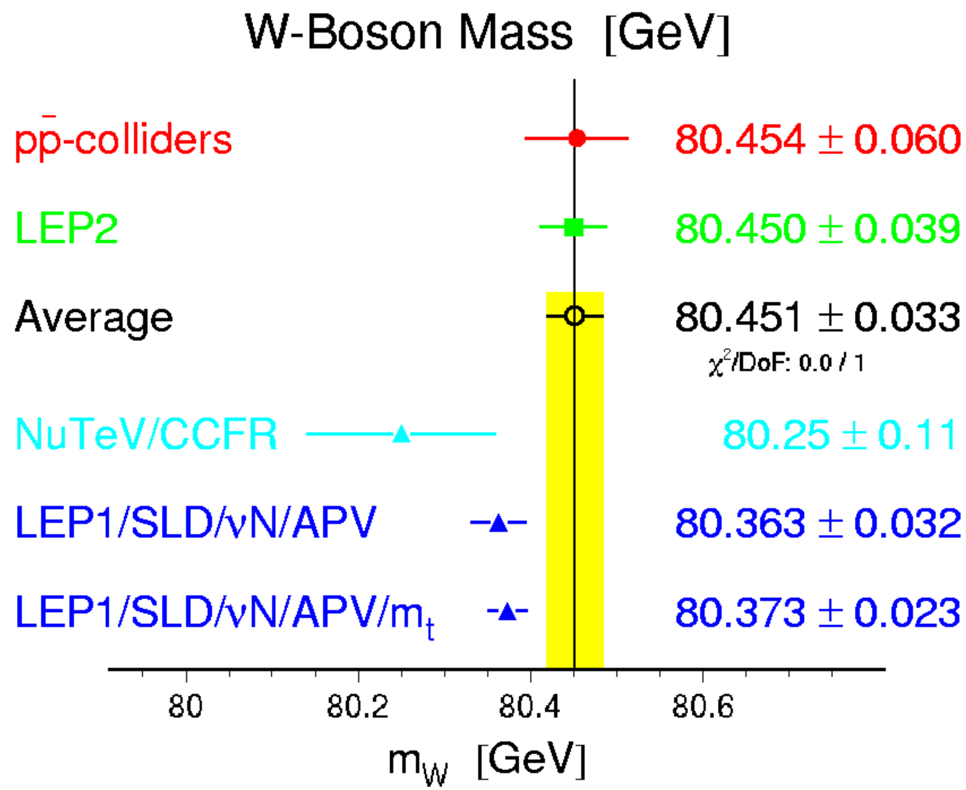
$m_W(qqqq) = 80.448 \pm 0.043$ GeV/c^2

$m_W(qql\nu) = 80.457 \pm 0.062$ GeV/c^2

Good compatibility between the two final state: $\Delta m = 9 \pm 46$ MeV/c^2

W mass at LEP 2: Result and Uncertainties





- Good consistency between experiments;
- Good consistency with hadron colliders (see Y.-K. Kim lecture);
- Good consistency with Z data (LEP/SLD).

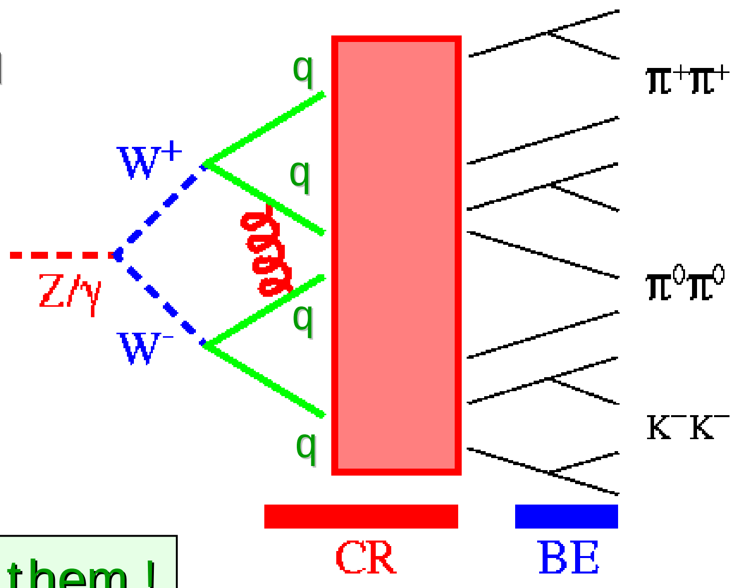
$$m_W(\text{LEP}) = 80.450 \pm 0.025 \text{ (stat.)} \pm 0.030 \text{ (syst.)}$$

Limited by systematic uncertainties on final state interaction (Bose-Einstein Correlation and Colour Reconnection).

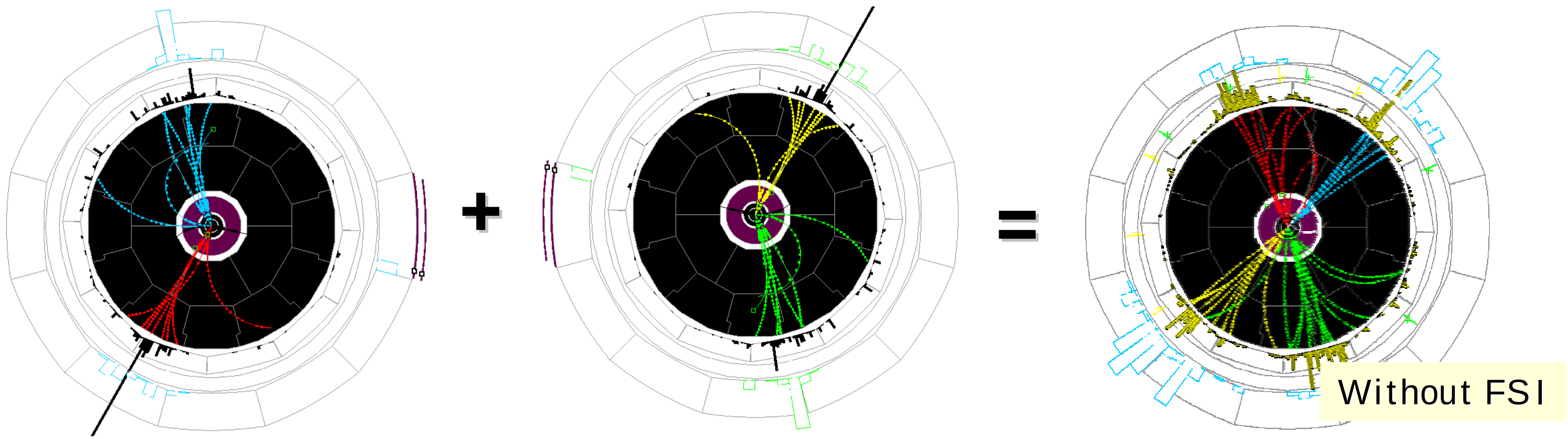
W mass at LEP 2: Final State Interactions

Interactions between W hadronic decay products may cause a shift between the mass from fully hadronic and semileptonic events:

- Colour Reconnection: QCD interaction between quarks from different W's; SMALL
- Bose-Einstein Correlations between identical hadrons (pions, kaons), well established in single W or Z decays. SMALL

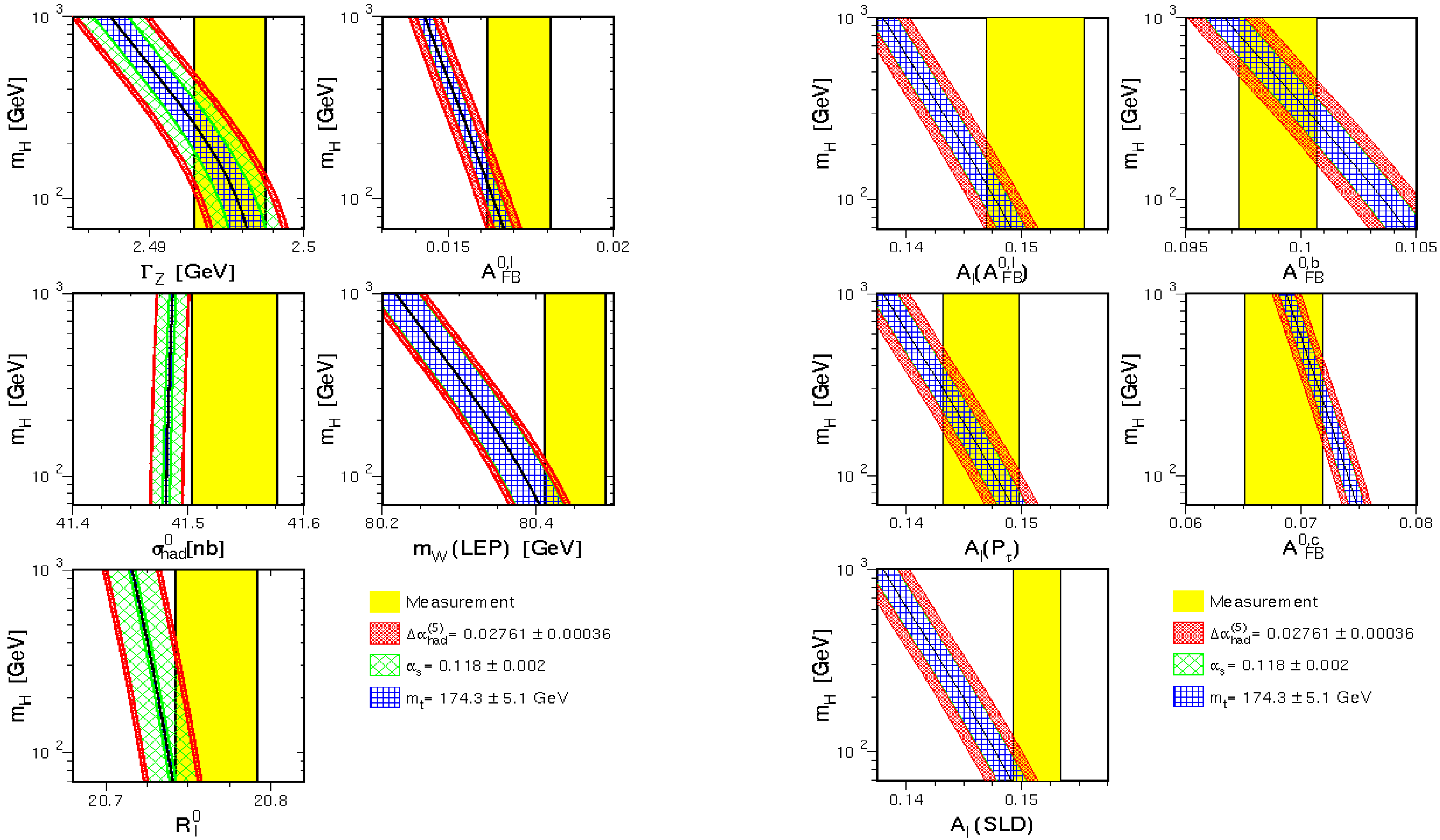


Use the data to constrain them !



Global Fit of the Standard Model to m_H (I)

Knowing m_{top}, most electroweak observables have a sensitivity to m_H through $\Delta\rho$

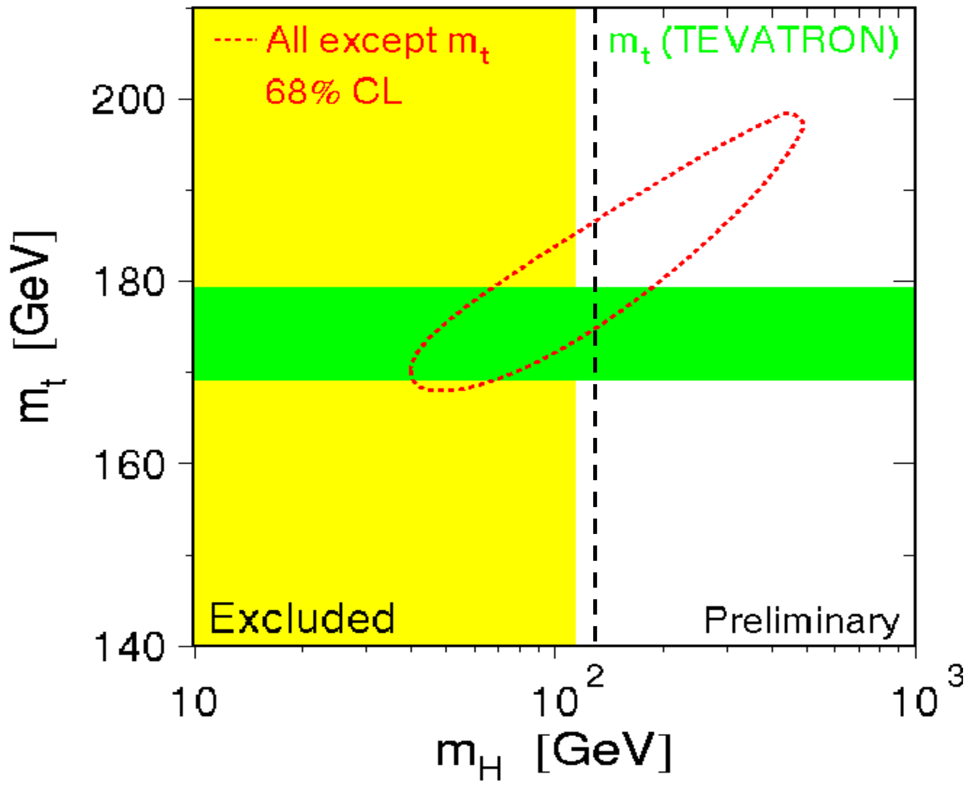


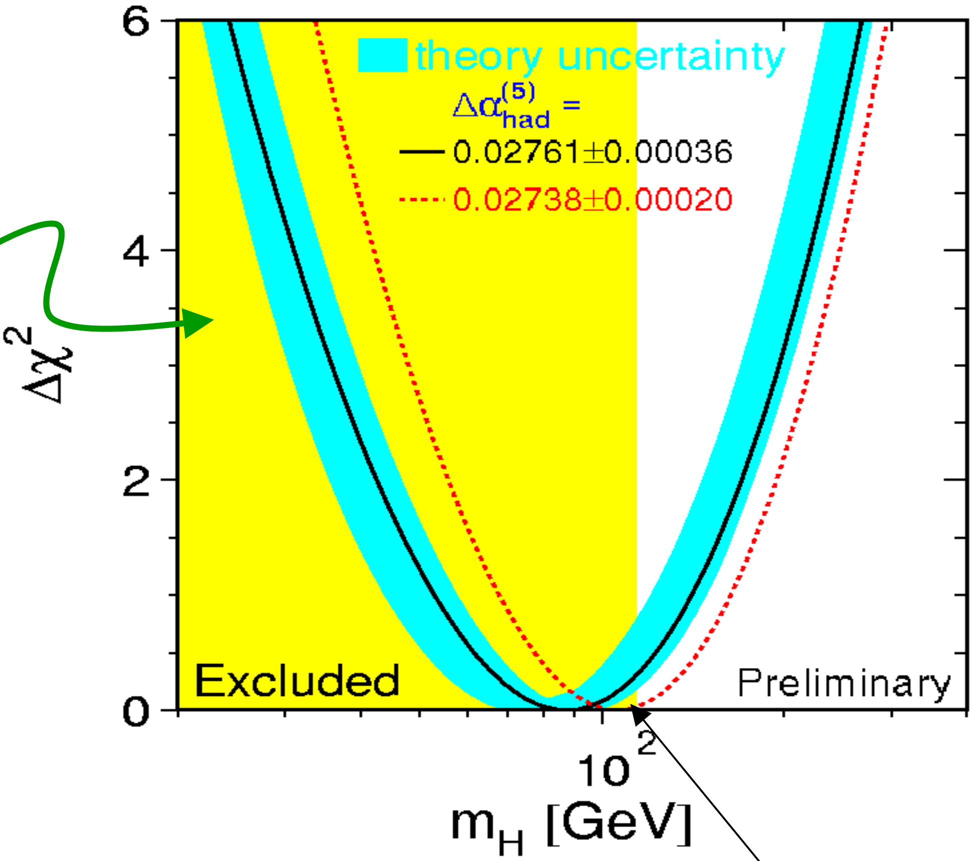
Global Fit of the Standard Model to m_H (II)

Global fit of m_H and m_{top}:

$$m_{top}^{EW} = 180.5 \pm 10.0\ \mathrm{GeV}/c^2$$

$$m_{top}^{direct} = 174.3 \pm 5.1\ \mathrm{GeV}/c^2$$





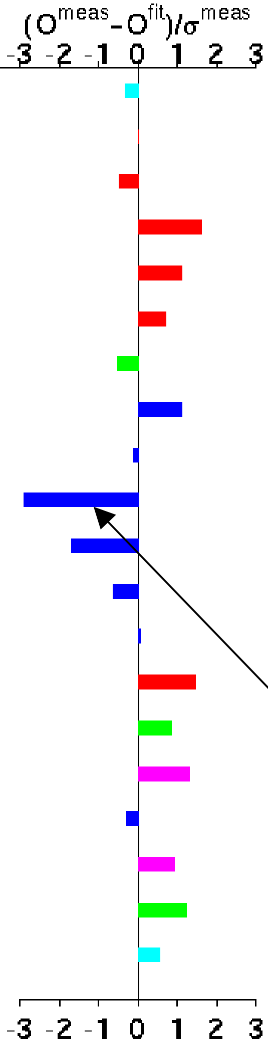
$$m_{Higgs}^{EW} = 108^{+57}_{-38}\ \mathrm{GeV}/c^2$$

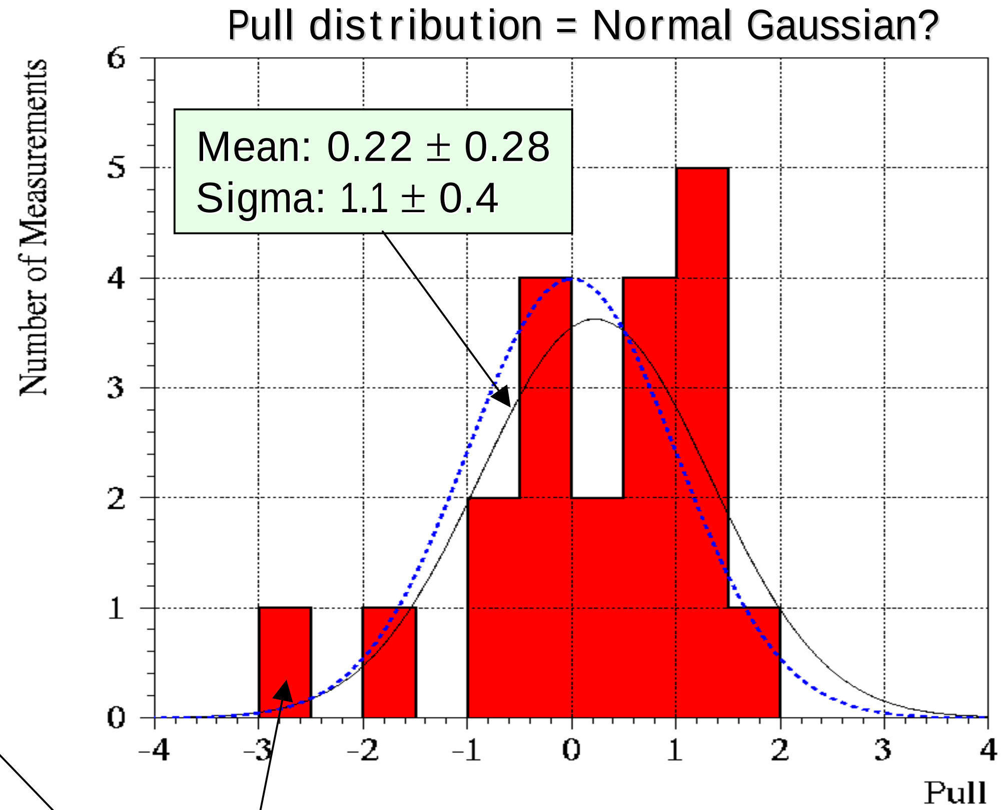
$$m_{Higgs} \leq 222\ \mathrm{GeV}/c^2 \text{ at 95\% C.L.}$$

Global Fit of the Standard Model to m_H (III)

Internal Consistency of the Standard Model?

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.35
m_Z [GeV]	91.1875 ± 0.0021	.03
Γ_Z [GeV]	2.4952 ± 0.0023	-.48
σ^0_{had} [nb]	41.540 ± 0.037	1.60
R_l	20.767 ± 0.025	1.11
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.69
$A_l(P_\tau)$	0.1465 ± 0.0033	-.54
R_b	0.21646 ± 0.00065	1.12
R_c	0.1719 ± 0.0031	-.12
$A^{0,b}_{fb}$	0.0990 ± 0.0017	-2.90
$A^{0,c}_{fb}$	0.0685 ± 0.0034	-1.71
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.47
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
$m_W^{(LEP)}$ [GeV]	80.450 ± 0.039	1.32
m_t [GeV]	174.3 ± 5.1	-.30
$m_W^{(TEV)}$ [GeV]	80.454 ± 0.060	.93
$\sin^2\theta_W(\nu N)$	0.2255 ± 0.0021	1.22
Q_W(Cs)	-72.50 ± 0.70	.56





Largest discrepancy (-2.9σ) well inside statistical expectation;

χ^2 probability = 8%. Just fine.

Global Fit of the Standard Model to m_H (IV)

What Next?

- Now: $\delta m_{top} = \pm 5.1$ GeV, $\delta m_W = \pm 34$ MeV

$$m^{EW}_{Higgs} = 108^{+57}_{-38}\ \mathrm{GeV}/c^2$$

- With $\delta m_{top} = \pm 2$ GeV

$$m^{EW}_{Higgs} = \ ?\ ^{+39}_{-28}\ \mathrm{GeV}/c^2$$

- With $\delta m_W = \pm 15$ MeV

$$m^{EW}_{Higgs} = \ ?\ ^{+43}_{-29}\ \mathrm{GeV}/c^2$$

- With $\delta m_{top} = \pm 2$ GeV and $\delta m_W = \pm 15$ MeV

$$m^{EW}_{Higgs} = \ ?\ ^{+21}_{-16}\ \mathrm{GeV}/c^2$$

1st Lecture Conclusions

- LEP and SLD allowed the internal consistency of the standard model to be tested with great precision;
- LEP and SLD checked the predictions of the Electroweak Symmetry Breaking mechanism (e.g., $m_W = m_Z \times \cos\theta_W$);
- LEP and SLD allowed the mass of the top quark to be predicted several years before it was discovered in 1995 at the Fermi National Laboratory;
- LEP and SLD measurements led to the prediction of a relatively small Higgs boson mass (around 100 GeV/c^2);
- Future Machines (Tevatron, LHC, LC) will be important for EW Physics.